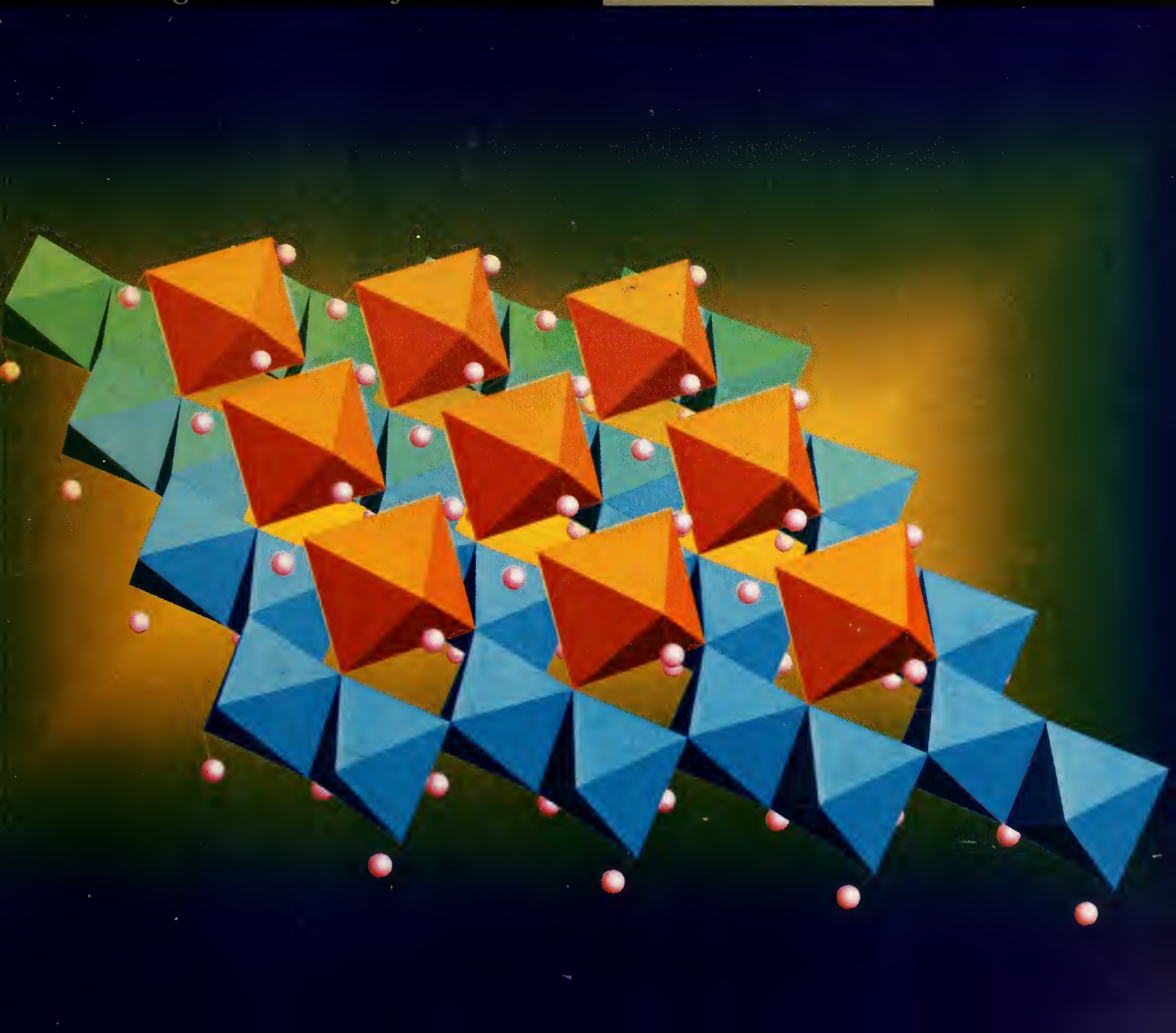


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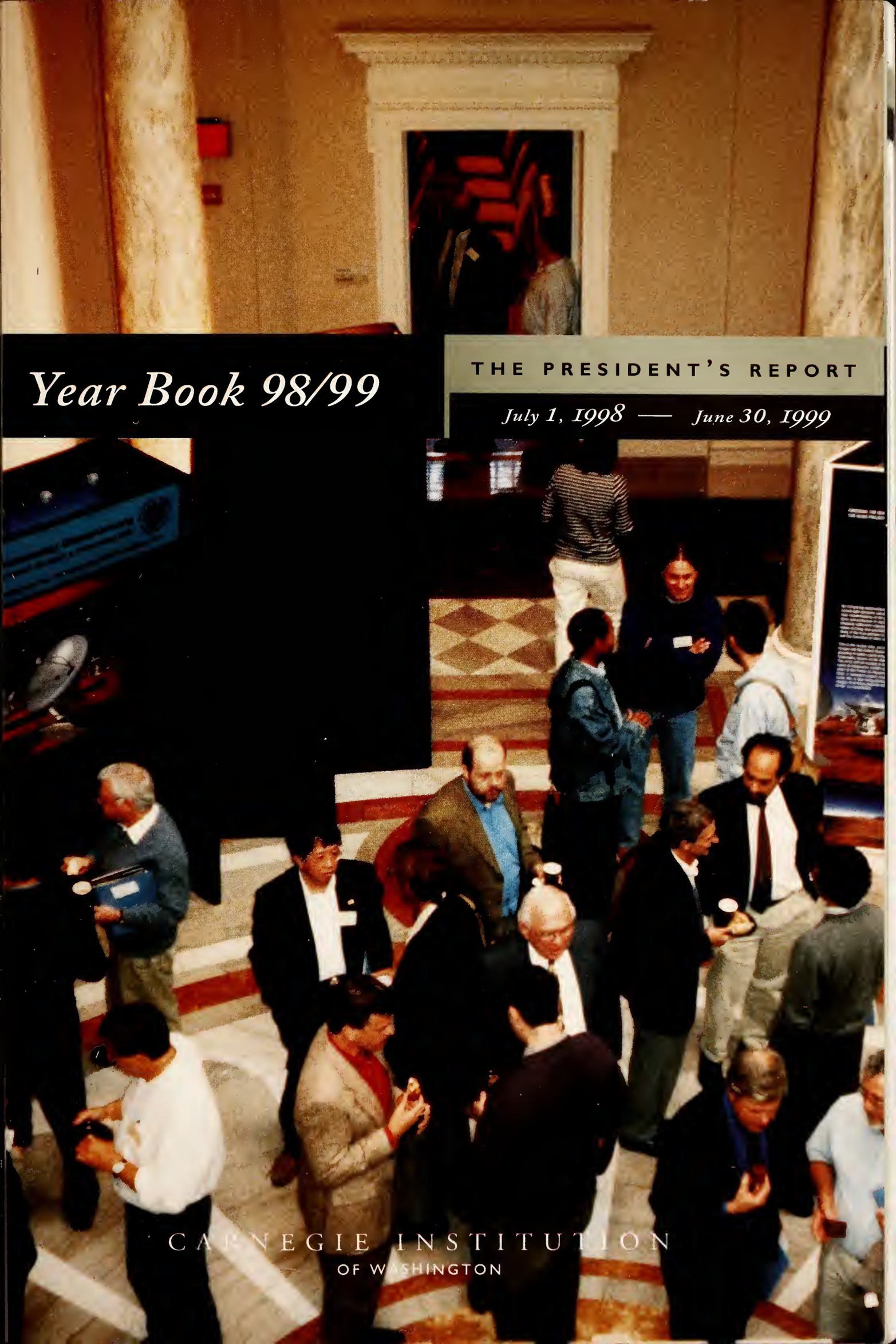
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On the cover: Above: Microtubule structures formed in *Xenopus* egg extract are revealed by immunofluorescence analysis. (Courtesy Yixian Zheng, Carnegie Department of Embryology.)

Below: This image shows the crystal structure of Phase D, $MgSi_2H_2O_6$. The orange octahedra represent MgO_6 and the blue ones, SiO_6. This material has the highest known pressure-temperature stability of any hydrous silicate and may be present as a mineral in Earth's lower mantle. (Courtesy Charles Prewitt, Carnegie Geophysical Laboratory and David Palmer, The Open University, U.K.)



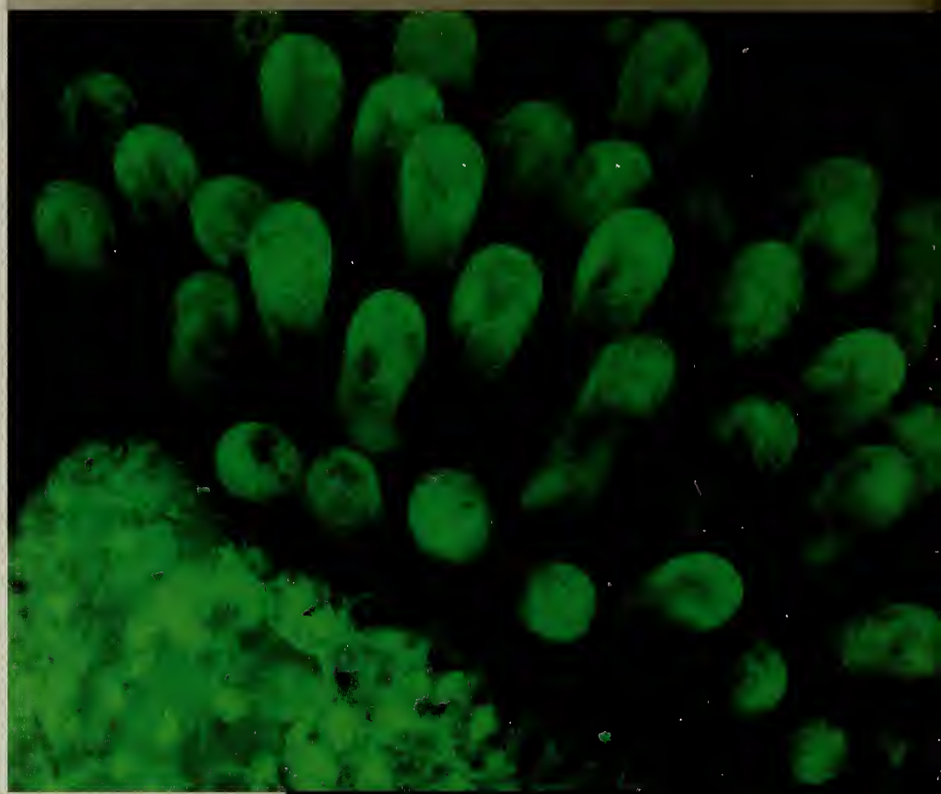
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THE PRESIDENT'S REPORT

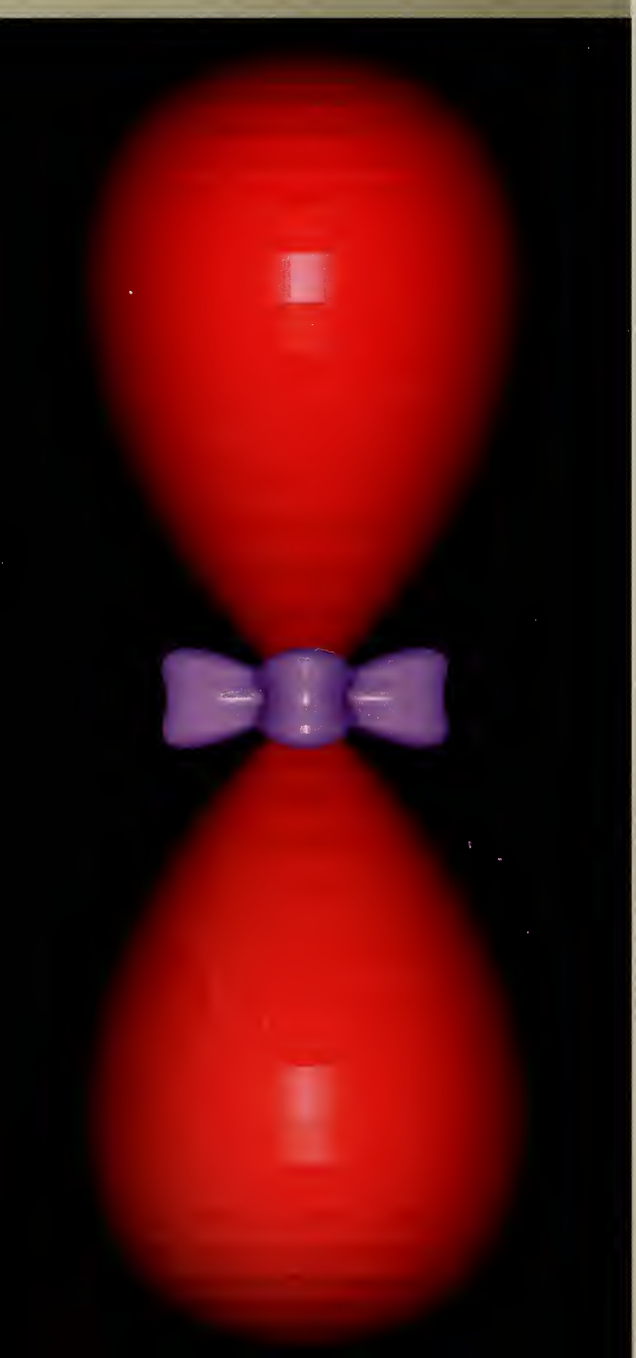
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ABOUT CARNEGIE

. . .TO ENCOURAGE, IN THE BROADEST AND MOST LIBERAL MANNER, INVESTIGATION, RESEARCH, AND DISCOVERY, AND THE APPLICATION OF KNOWLEDGE TO THE IMPROVEMENT OF MANKIND . . .

The Carnegie Institution of Washington was incorporated with these words in 1902 by its founder, Andrew Carnegie. Since then, the institution has remained true to its mission. At five research departments across the country, the scientific staff and a constantly changing roster of students, postdoctoral fellows, and visiting investigators tackle fundamental questions on the frontiers of biology, earth sciences, and astronomy.

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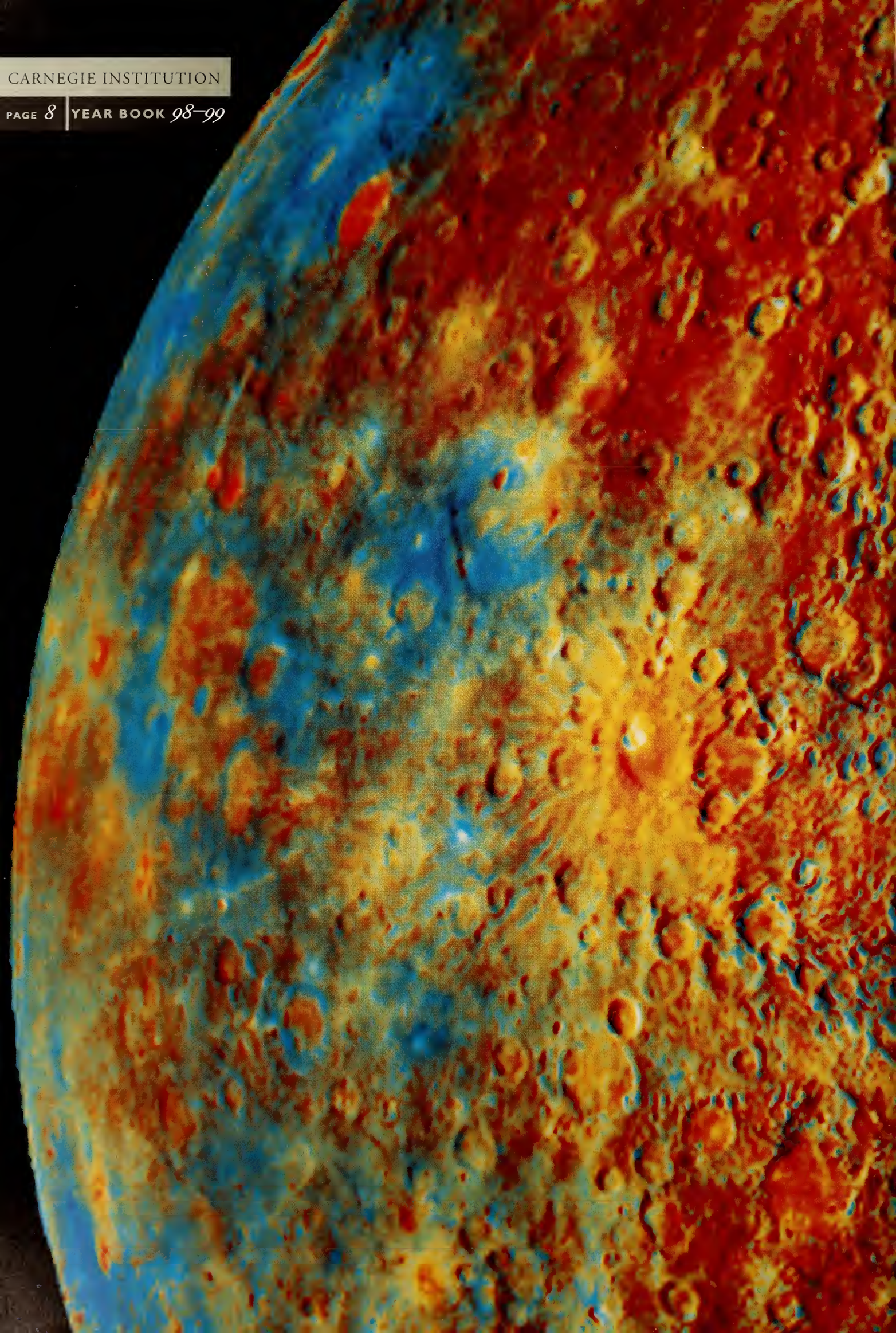
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The President's Commentary

"IT HAS SEEMED ALL DAY AS THOUGH MY HORIZON WAS NOT BIG ENOUGH TO HOLD ME.
THIS MEANS THAT MY SOLE AMBITION FOR ME [THESE] LAST [FEW] YEARS IS ABOUT TO BE REALIZED.
RARELY, I THINK ARE AIMS SO CLEARLY DEFINED IN LIFE AS MINE HAVE BEEN.
EVER SINCE VISITING CHICHÉN ITZÁ 7 YEARS AGO ...
IT HAS BEEN MY FONDEST WISH TO SOMEDAY EXCAVATE THAT CITY."

FROM THE DIARY OF SYLVANUS G. MORLEY, JANUARY 16, 1914,
THE DAY HE WAS NOTIFIED OF HIS APPOINTMENT TO THE CARNEGIE INSTITUTION OF WASHINGTON.

A goal of this institution is to demonstrate, through excellence and originality, the nature of scientific research and its value to society. As implied by Vannevar Bush's phrase, "the endless frontier," it is a goal without inherent limits, though it is constrained by the realities of time and resources. Carnegie's trustees and charter do not tell us how to reach that goal. The one directive was given by Andrew Carnegie in his Trust Deed of January 28, 1902: "To discover the exceptional man in every department of study whenever and wherever found, inside or outside of schools, and enable him to make the work for which he seems specially designed his life work." As might be expected, my personal sensibilities have trouble with the exclusively male noun and pronoun. But with slight modifications, Carnegie's remarkable statement remains pertinent and inspiring.

To some, the phrase "exceptional person" implies the solitary scientist, who develops personal ideas and works with her or his own hands. Our vision of the institution surely includes the nurturing of such people. But any too rigid a vision would confine our opportunities to attain the goal. Caryl Haskins expressed a broader vision when he wrote: "That high mobility within specific fields, that the unfettered crossing of fields, that the fashioning of unconventionally wide-ranging research programs, are subject only to the limitations imposed by Nature and by the judgements of gifted and discriminating investigators, and that making this mobility and flexibility possible is a principal objective of the Institution."[1] Operationally and institutionally, the central word is "flexibility." Originality and excellence as well as the ideas of exceptional people will flourish under many circumstances.



Sylvanus Morley (right) is photographed on the expedition of 1915. He identified this picture only as "Scene in Camp." The other men are local workers who accompanied Morley.

I was stimulated to think about these issues by the growing participation of Carnegie scientists in very large projects. Science is a pragmatic and opportunistic venture. Contemporary science often requires the collaboration of large numbers of people and very substantial resources. Typically, if there is anything typical about research, such enterprises bring Carnegie scientists into elaborate cooperative consortia with colleagues from other institutions. Some of the projects depend on costly facilities that are provided and managed by federal agencies. Even the word "managed" makes the projects questionable in some minds. How can we decide if these projects are consistent with Carnegie's directive? The appropriate measures are the originality and excellence of the science as well as the opportunity for the Carnegie scientist to develop her or his ideas.

1 Haskins, C. P., ed., *The Search for Understanding*, xvii, Carnegie Institution of Washington, Washington, D.C., 1967.

Left: The planet Mercury is shown here. (Image courtesy of the Johns Hopkins University, Applied Physics Laboratory.)

THE INDIVIDUAL SCIENTIST

As a small institution, we hold that our limited resources can make the largest and most distinctive contribution by providing for the maximum independent initiative by Carnegie scientists. In research institutions less capable of support, scientists are of necessity more prone to undertake research that is consistent at any given time with the aims of federal or private funding sources. Carnegie's unique position reflects decisions by generations of trustees to keep the institution small in order to sustain its independence. The massive growth of research universities over the last 50 years relied heavily on resources provided by the federal government. However, the customs and practices of these research universities, and of their now huge scientific communities, have a common origin with those of this institution. Even today, in an era of many team efforts, the scientific community and university administrators still require the evaluation of individual scientists' accomplishments. University appointment and promotion committees struggle to identify an individual's contribution to multiauthored papers even when that is next to impossible. Individual contributions are formally recognized by the many prizes awarded for outstanding scientific work; almost always some collaborators are left out. The ideas and competence of individual scientists, as reflected in their grant proposals, are evaluated by peer review groups. The Carnegie Institution is similar in this respect. Regardless of the number of collaborators, our institution values the role of the individual investigator "suitably endowed and suitably protected, whose time, quite literally, is bought by the Institution and then returned as unconstrained endowment."[2] We do want to know that our scientists are and remain intellectually suitably endowed and productive.

COLLABORATIVE PROJECTS

And yet, large, collaborative, and expensive projects have been part of the institution's programs since its earliest days. The scientific question might be formulated by one person, but making the research happen requires many people and various skills. The nonmagnetic ship *Carnegie* and its many voyages over 20 years was such a venture; it was proposed and promoted by L. A. Bauer, first director of the Department of Terrestrial Magnetism. Another scientist with a large vision was Sylvanus G. Morley. In 1914-15, the institution provided him with $3,000 to begin a survey of Mayan sites in Central America. Morley tramped the jungles for a decade and his annual support rose slowly, reaching $31,000 in 1924, when he recommended extensive excavations at Chichén Itzá and a few other sites. By the 1930s, and in spite of the financial difficulties brought on by the depression, Morley's project was receiving $150,000, more or less, each year for excavation and preservation of the artifacts. No longer a lone surveyor, his group grew to seven Carnegie Staff Members and a large number of laborers. Many hands and heads were needed to realize one man's dream. And the dream was only a starting point. Neither Morley nor anyone else could have predicted at the start just how much the expeditions would reveal. As huge as the undertaking was, it was small compared with what is needed today to undertake certain ripe and remarkably interesting projects.



The nonmagnetic ship *Carnegie*, which took magnetic measurements between 1909 and 1929, is shown here in full sail.

2 *Ibid.*

A voyage to the planet Mercury is one such project. In the summer of 1999, Sean Solomon learned that NASA approved the proposal made by him and a consortium from 12 other institutions for a mission to Mercury. The craft will depart in 2004 and arrive in orbit around the planet in 2009 after two flybys of Venus and two of Mercury itself. A lot of the challenge and expense of the new project is in the engineering and construction of the space probe and the scientific instruments. The majority of the almost $290 million cost will be spent at the Applied Physics Laboratory (APL) and several firms. But the point of the whole thing is to answer basic questions about the innermost planet of the solar system. As chief scientist and principal investigator, Solomon will provide the leadership. To what extent is this Solomon's science in the sense that the Chichén Itzá excavation was Morley's science?

The *Mariner 10* mission in 1974 and 1975 was the last and only time Earth visited Mercury. Unlike Morley, Solomon could only reconnoiter his target by tramping in his own mind. He began to formulate his research plan for Mercury 25 years ago, soon after the *Mariner 10* mission. He wrote that the remaining fundamental questions then included, "Why is Mercury so different from the other terrestrial planets in bulk composition, geological evolution, and magnetic field? To what extent are those differences attributable to the planet's proximity to the Sun or to some other explanation?" He collaborated in devising a scientific strategy for further exploration of the planet, although the required technology did not exist. That is where things stood until a few years ago when the Applied Physics Lab came up with a feasible technical plan for a Mercury orbiter.

Solomon's published ideas as well as his experience with a Venus mission in the intervening years made him an obvious candidate for scientific leadership. Together, Solomon and APL recruited additional members for the science team. These other scientists contributed their own ideas and then Solomon defined the scientific goals and rationale, including the six core questions the mission will address. These questions reflect those Solomon set out more than 20 years ago: What is



Department of Terrestrial Magnetism Director Sean Solomon is pictured with a model of the MESSENGER craft.

the origin of Mercury's high density? What are the composition and structure of its crust? Has Mercury experienced volcanism? What are the nature and dynamics of its thin atmosphere and Earth-like magnetosphere? What is the nature of its mysterious polar caps (are they made of water ice or sulfur or something else)? Is a liquid outer core responsible for generating its magnetic field?

THE INDIVIDUAL AS COLLABORATOR

To what extent does Solomon's role in the new mission to Mercury reflect our institutional expectations of the individual scientist? Solomon will acquire data to help answer questions he has long pondered: What can we learn about how Mercury was formed, and how has the planet's surface been modified by volcanic and tectonic processes? Other scientists will concentrate on other questions, including those concerning the planetary atmosphere and magnetosphere. Like Morley, who recruited experts in hieroglyphs, architecture, ancient agriculture, and ceramics, Solomon's collaborators will help him make the most of the freedom he has as a Carnegie scientist by taking advantage of the extraordinary opportunity NASA is providing to scientists interested in our solar system. His initiative and management of the mission mark Solomon as an exceptional individual in one sense. But the crux of the matter relates to his science.

The Mercury project, dubbed MESSENGER, is just beginning. Carnegie astronomers have, for almost a decade, provided leadership to another huge endeavor that is now nearing completion: the Key Project of the Hubble Space Telescope, the evaluation of the Hubble constant. Edwin Hubble's name is attached to this constant number, H, because he was first to recognize that the velocity, v, with which objects in the universe move away from us increases in proportion to the object's distance, d, from us. Thus, v = Hd. Publications reporting the results of the Key Project typically have more than 20 authors. In what way was the science driven by the Observatories' Staff Member Wendy Freedman, who is described in NASA announcements and the press as the team leader?



Wendy Freedman is an Observatories Staff Member and leader of the Hubble Space Telescope Key Project on the Extragalactic Distance Scale.

As a graduate student, Freedman had used Cepheid variable stars to measure the distances to nearby galaxies. This was an established method for determining the distance scale of the universe, and thus the distance, d, of objects. The distance scale needs to be known with confidence if the Hubble constant, H, is to be evaluated. Newly available technologies allowed Freedman to correct errors inherent in earlier methods, including the nonlinearity of measurements of brightness on photographic plates and the effect of galactic dust, which make the Cepheids appear fainter and thus farther away than they really are. She, often in collaboration with her husband, Barry Madore, continued to refine the methods when she came to the Carnegie Observatories, first as a postdoctoral fellow and later as a Staff Member. In 1984, she presented new results on the distance scale at a meeting where it was also announced that plans for Hubble Space Telescope science included a Key Project to evaluate the Hubble constant. Freedman joined with 10 other astronomers to prepare a proposal for the competition. She was a central figure in the group because she had unique experience with the new techniques and distance measurements. By 1990, when, after long delays in the launch time, the Space Telescope Science Institute finally accepted proposals, Freedman had become the chief scientist on the project. In the intervening years, she and Madore had refined techniques to enhance the efficiency of the observations and thus significantly decrease the required telescope time. The proposal was successful, and data collection began in 1991. By 1994, the science and the management of the project had become complex and time consuming, and more scientists joined. More than 27 people were finally involved, including Madore, now a Senior Research Associate at the Observatories, and DTM Staff Member John Graham, both of whom were two of the original team members.



This is galaxy NGC 4603, the most distant galaxy to date in which Cepheid stars have been found.

In this instance, Freedman had laid the groundwork for an improved approach to a long-standing

problem of fundamental interest to all astrophysicists. The Hubble Telescope was essential if she was to advance her scientific interests. That requirement necessitated joining a national effort in which scientific and technical managers played critical roles and a score of astronomers were kept busy. The complexity of the research, its scientific importance, and public interest in the outcome made it essential to have many people bring different skills and talents to the problem, if the precious time on the telescope was to be well used. Again, the analogy with Morley's Earth-bound science is striking. For Freedman, as for Morley and Solomon, personal scientific questions defined the road map for exploration.

The mission to Mercury and the Hubble Key Project have in common a dependence on large, very expensive instruments that cannot be built, maintained, or operated by single institutions. The Las Campanas Observatory defines the largest such facility that the Carnegie Institution could reasonably undertake. Few other private institutions can match what generations of Carnegie astronomers and trustees have built at Las Campanas. In the last few years, with the construction of the Magellan telescopes, we have recognized that if we are to exploit in the future the opportunities for modern research provided by Las Campanas, we cannot do it ourselves. New science demands new, complex, and costly technology. Collaborators and consortia are necessary if Las Campanas is to be a significant source of new science in the new century. We will regret the loss of the unique independence and informal style of Las Campanas. Miguel Roth and the mountain staff will strive to sustain the spirit of the place in the new situation. But to do original and excellent science, change will be necessary, change that can, if we are not attentive, diminish the role of the exceptional individual.

COLLABORATIONS BRIDGE DISCIPLINES

Similar changes, on a much smaller scale, are occurring in other sciences. These are driven not so much by the need for enormous and expensive facilities as by the requirement for a variety of techniques and expertise to obtain answers to fundamental questions. Sometimes an individual investigator can educate herself to handle all the challenges. Other times, collaborations make sense. The need for collaborations or for learning new methods is a sign that research is bridging more than one traditional discipline. And often this signifies great originality. The probability of major advancements in understanding is increased when scientists cross disciplinary boundaries. The astrobiology initiative at DTM and GL is an example of such an interdisciplinary endeavor. An example in biology is the growing collaboration between computer scientists and biologists directed at understanding the sequenced genomes of many organisms. At the Department of Plant Biology, Chris Somerville is establishing a new program in bioinformatics, which will adapt new computer technology for the study of the genome of the model plant, *Arabidopsis*. Allan Spradling has helped to foster similar developments through his participation in the *Drosophila* community, although the work itself is not part of the program at the Department of Embryology. The ecological studies of Chris Field and Joe Berry at Plant Biology are also highly dependent on computer modeling. Biological studies increasingly cut across disciplinary lines that were once quite rigid.

These changes in the way Carnegie science is done are evident in the bibliographies in the recent



Chris Field (left) and Joe Berry

Carnegie Year Books. As many as 25 authors are listed on the papers reporting the results of the Hubble Key Project. Few papers have single authors. Alan Boss and George Wetherill, both of whom model aspects of solar system and planet formation, publish on their own, as do others on occasion. Most papers have five or fewer authors. Counting papers on which Staff Members are authors, the averages are 3.6, 4.8, 3.3, 4.7, and 3.0 for Embryology, the Observatories, the Geophysical Lab, Plant Biology, and DTM, respectively (omitting the few papers with more than 15 authors). Frequently, the additional authors are scientists in other institutions.

In the two biology departments, the coauthors are usually postdoctoral fellows or graduate students. These two departments, which have the smallest number of Staff Members, have the highest number of postdoctoral fellows per Staff Member: four in Embryology and three in Plant Biology. But the number of postdoctoral fellows per Staff Member is related less to the small number of Staff Members than to the dependence of modern biological research on intensive, time-consuming experimental work and the many different techniques required for definitive answers to the questions being asked. The modern biologist can no longer simply be a geneticist, a cell biologist, a physiologist, a microscopist, a biochemist, or an ecologist. Many of the most original investigations require that a scientist be many of these simultaneously or engage the collaboration of those who can contribute the needed skills.

LARGE LABS ARE NOT NECESSARILY BETTER LABS

It is not only at Carnegie that independent investigators such as our Staff Members orchestrate the activities of a group. Groups in other institutions are frequently much larger than ours, though not necessarily as productive. More than 10 years ago, public discussion of concerns about the growing size of research groups in biology was initiated by Bruce Alberts.[3] At the time, Alberts was professor of biochemistry at the University of California, San Francisco. Now he is president of the National Academy of Sciences. Alberts argued that large research groups were inefficient because they increased the time that the leader had to spend on nonintellectual endeavors such as raising funds and finding jobs for members of the group, thereby leaving less time for thinking and reading. Alberts also said that large laboratories are a "poor training environment" for preparing young scientists for independent research careers. He provided only a couple of hints regarding his definition of a large laboratory. It seems to lie somewhere between 5 and 15 members. Staff Members at the two Carnegie biology departments have, on average, smaller groups than Alberts's lower limit. But before we take any comfort in that, we should consider the other side of the picture. That other side was expressed in responses to Alberts from two other distinguished biologists.

Paul Schimmel thought Alberts's statement was simplistic. Schimmel reviews the many different kinds of technical competencies and number of operations required to carry out certain biological investigations and concludes, "For some projects, the research simply demands a scale that is larger —for reasons of effectiveness and efficiency."[4] A few weeks later, Jan Klein of the Max-Planck-Institut für Biologie in Tübingen weighed in with a more extreme view: "What these many complainers do not seem to understand is that large research groups have become a historical necessity ... If a small laboratory could afford all this [necessary] equipment, it would not be able to use it efficiently. It would be comparable to a farmer who has acquired a combine to harvest ten acres of land. Only in a large laboratory can questions requiring multifaceted approaches be posed [and answered]."[5] Klein has a point, but only if one examines his assumptions. The large laboratory he describes seems to stand alone, with little communication or sharing with nearby colleagues. He fails to recognize that mutual collegiality can also enlarge the intellectual and instrumentational competencies of small groups. Perhaps shared

3 Alberts, B., Limits to growth: in biology, small science is good science, *Cell 41*, 337-338, 1985.
4 Shimmel, P., In biology, neither smaller or larger is necessarily better, *Cell 42*, 1, 1985.
5 Klein, J., Big may not be beautiful, but it is necessary, *Cell 42*, 395-396, 1985.

instruments and facilities were not part of his institution's traditions, as they are at Carnegie labs. In spite of their small size and small groups, the Carnegie biology labs have demonstrated that multifaceted investigations can be carried out by small groups with extraordinary success and efficiency. Moreover, though it might seem counterintuitive to some, the independence of individual investigators can thrive in a cooperative scientific community.

THE ROLE OF POSTDOCS

At Carnegie as well as in larger biology laboratory groups, much depends on the hard, sometimes tedious work of postdoctoral fellows and associates. The overall goals of the research project are generally those of the senior scientist, vetted through the peer review of a granting agency. What do the students and postdoctoral fellows gain in return for their long hours at the bench and adherence to the general program set by someone else? First of all, they should acquire new knowledge, expertise, and insights into how to define, shape, and carry out research projects. In the best of circumstances, they, together with their mentors, form lively collegial groups that generate new questions and approaches in the framework of the established goal. If they are lucky enough and smart enough, the young scientists may discover something that changes the direction of the whole project. The science benefits from their youthful iconoclasm. What happens to the Staff Member, one of Carnegie's exceptional people, in the organization of modern biological research? The outcome of each research project is the result of the thinking, analysis, and hard work of a group of at least two people: the Staff Member, serving as mentor, and one student or postdoc. Even the participants may find it difficult to sort out who had which important idea, and if their relationship is healthy, they don't spend a lot of time worrying about it. But the initial input, the framing of the question, the general road map, these more than likely reflect the vision of the individual exceptional person.



Shauna Somerville (left) with postdoctoral fellow John Vogel.

In the physical sciences, postdoctoral fellows are more frequently independent researchers, interacting as colleagues with other postdocs and Staff Members, but not necessarily as collaborators on a particular project. That accounts, at least in part, for the fact that at the Observatories, the Geophysical Lab, and DTM the numbers of postdoctoral fellows and Staff Members are about equal.



Observatories' postdoctoral fellows and associates. Front row, from left: Swara Ravindranath, Lin Yan, Jason Prochaska, and Scott Trager. Back row, from left: Ben Weiner, Ron Marzke, and Scott Chapman.

Flexibility remains essential in the organization and management of any institution for research. At Carnegie, flexibility is assured by the independent operations of the five departments and by emphasis on the freedom of individual scientists to follow their own lights.

—Maxine F. Singer
November 1999

LOSSES

Richard Black, manager of grants and resources at the Observatories, died February 5. He was with Carnegie for over 20 years.

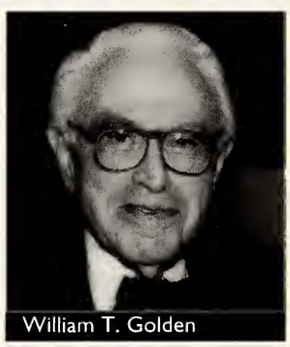
Rudy Warren, a longtime employee at the Department of Plant Biology, died this past spring.

Andy Antoszyk died on March 21. He was the machine shop foreman at the Geophysical Laboratory and had been with Carnegie since 1980.

James Thomas, animal-care technician for the Department of Embryology, died on November 11. James came to the department in 1994.

RETIRING

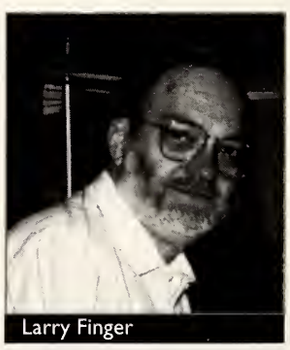
William T. Golden stepped down from the board after 30 years of service to become a trustee emeritus. The board honored him for his years of service by naming the Observatories' auditorium in Pasadena, California, the William T. Golden Auditorium.


William T. Golden

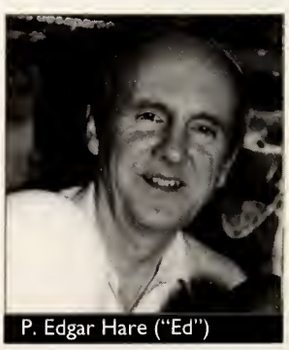
Four trustees were named senior trustees: **Gerald D. Laubach, John D. Macomber, Frank Press,** and **Sidney J. Weinberg, Jr.**

Olle Björkman retired from the Department of Plant Biology in July. He was guest of honor at a symposium in August that highlighted some of the areas where his research on plant physiology has had an impact. Held in California's wine country, the symposium was attended by nearly 50 of Olle's friends, students, and colleagues.

Larry Finger, a Geophysical Laboratory Staff Member since 1969, retired in July. He arrived at the lab in 1967 as a postdoctoral fellow and was appointed staff crystallographer two years later. A symposium to honor him and **Charles Prewitt** was held at the administration building in April. It was entitled "Mineralogy at the Millennium" and was attended by over 135 participants. The event identified a number of new opportunities in experimental and theoretical studies of Earth and planetary materials, areas in which Larry and Charlie have had major influence worldwide.


Larry Finger

P. Edgar Hare ("Ed") retired from the Geophysical Laboratory in October 1998. A conference was held in his honor at the American Geophysical Union headquarters in April 1998. The conference, entitled "Perspectives in amino acid and protein geochemistry," was a great success and a fitting tribute to Ed's significant scientific contributions.


P. Edgar Hare ("Ed")

Aida Wells, Department of Plant Biology secretary/receptionist for more than 20 years, retired in September 1999.

Brian Welsh, mechanical engineer at the Department of Plant Biology, retired in June.

Joan Gantz, Observatories' librarian since 1976, retired on June 30.

GAINS

The board elected **Tom Cori** as a new trustee at its May meeting. Dr. Cori is the chairman and CEO of Sigma-Aldrich Corporation in St. Louis, Missouri.


Tom Cori

Jaylee Mead was elected to the board of trustees at the May board meeting. Dr. Mead is a Washington, D.C., resident and a retired astronomer from NASA Goddard Space Flight Center. She is very active in the Washington arts and philanthropy.


Jaylee Mead

Paul Butler is the newest Staff Member at DTM. He was previously with the Anglo-Australian Observatory in Sydney, Australia. Along with his colleague Geoff Marcy, Paul has discovered two-thirds of the known extrasolar planets, including the only known system of multiple planets orbiting a Sun-like star.

Two new Staff Members joined the Observatories this year. **John Mulchaey** received his Ph.D. in 1994 from the University of Maryland. A former Carnegie Fellow at the department, his work focuses on galaxies and their clustering. **Michael Rauch** received his Ph.D. in 1993 from Cambridge University. He is a former Observatories postdoctoral fellow; his studies include QSO absorption-line systems and the large-scale structure of the universe. At Las Campanas in July 1998, **Mark Phillips** was appointed Associate Director.

Mikhail Eremets is a new Senior Research Scientist at the Geophysical Laboratory. He is working in the field of high-pressure research with Dave Mao and Rus Hemley.


Paul Butler

Terence Murphy is the newest Staff Associate at Embryology. His work focuses on chromosome inheritance and epigenetic aspects of centromere function.

Tina McDowell succeeded **Pat Craig** as editor and publications officer in February. Tina comes to Carnegie from Time-Life Books, where she was editorial director for science, nature, and health.

TRANSITIONS

François Schweizer, a DTM Staff Member since 1981, has transferred to the Observatories, where he will continue his work in observational astrophysics, the structure and evolution of galaxies, and the cosmic distance scale.

HONORS

Trustee **Sandra Faber** was elected a fellow of the California Academy of Sciences.

The 1999 Harvard Business School Alumni Achievement Award was given to trustee **Bruce Ferguson** at a ceremony in June.

Richard Meserve, also on the board, was confirmed by the Senate in October to be the new head of the Nuclear Regulatory Commission.

Trustee **William Rutter** received the Biotechnology Hall of Fame special recognition award in October 1998.

Charles Townes, trustee emeritus, received the Mendel Medal from Villanova University.

Maxine F. Singer received the Vannevar Bush Award from the National Science Board of the National Science Foundation in May. The award was established in 1980 to honor the leadership of a distinguished senior scientist and statesperson. It is the highest honor bestowed by the board, and Dr. Singer is the first woman ever to receive it.

Wesley T. Huntress, Jr., director of the Geophysical Laboratory, was reelected president of the American Astronautical Society and was appointed a distinguished visiting scientist at the Jet Propulsion Laboratory. Huntress also received the Caltech Management Association's Excellence in Management Award for 1999.

Sean Solomon, director of the Department of Terrestrial Magnetism, was the 1999 recipient of the G. K. Gilbert Award from the Geological Society of America. This award is presented annually for outstanding contributions to the solution of fundamental problems in planetary geology. Solomon also received a fellowship from the Japan Society for the Promotion of Science to visit and give lectures at the Earthquake Research Institute, the Ocean Research Institute, the Institute of Space and Astronautical Science, the universities of Tokyo, Hokkaido, and Kyushu, and the annual meeting of the Japanese Society for Planetary Sciences.

Winslow Briggs, Director Emeritus at Plant Biology, received two lectureship awards. He was selected as the Anton Lang Memorial Lecturer at Michigan State University in March, and was chosen to give the Philip C. Hamm Memorial Lecture at the University of Minnesota in May.

Staff Member at Embryology **Joe Gall** received the J. E. Purkinje Honorary Medal for Merit in the Biological Sciences awarded by the Academy of Sciences of the Czech Republic.

Marnie Halpern, Staff Member at Embryology, was elected to the board of directors of the Society for Developmental Biology as the junior faculty representative.

Jimo Borjigin, a Staff Associate at Embryology, received the John Merck Scholarship in the Biology of Developmental Disabilities in Children.

Alejandro Sánchez Alvarado, Staff Associate at Embryology, received the Marcus Singer Medal for research in regeneration at the Midwest Society for Developmental Biology in May.

The American Society for Cell Biology's Women in Cell Biology Committee has awarded Embryology Staff Member **Yixian Zheng** its 1999 Junior Award. The award is one of the top honors from the society, and it recognizes Yixian's outstanding scientific contributions using *Xenopus* and *Drosophila* systems.

Observatories Staff Member **Alan Dressler** received NASA's Medal for Public Service in recognition for his "extraordinary scientific leadership in developing the NASA Origins theme by producing the report, 'Exploration and the Search for Origins,' and communicating it brilliantly."

The lodge at Las Campanas was named in honor of **Horace Babcock**, emeritus member of the Observatories and former director of the then jointly operated observatories of Carnegie Institution and Caltech from 1964 to 1978. Babcock arrived at Carnegie as a Staff Member in 1946; while director of the Observatories he was one of the leaders in Carnegie's founding and early development of the Las Campanas Observatories.

Bill Pike, a Geophysical Laboratory summer intern in 1998, was awarded the 1999 Geological Society of America Stephen E. Dwornik Student Paper Award for his paper entitled "Melting temperatures in the Fe-Ni-S system at high pressures: implications for the state of the Martian core." This research was done in collaboration with Yingwei Fei and Connie Bertka. **Alexander Berengaut**, also a lab intern and a high school student, worked with Connie Bertka on a project entitled "The formation of symplectic exsolutions in Martian meteorites: implications for the petrologic history," and was a semifinalist in the Intel Science Talent Search. He also represented Montgomery County, Maryland, at the International Science Fair.

Toward Tomorrow's Discoveries

The Carnegie Institution received gifts and grants from the following individuals, foundations, corporations, and government agencies during the period from July 1, 1998, to June 30, 1999.

CORPORATIONS AND FOUNDATIONS

$100,000-$1 million

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Arcana Foundation, Inc.
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More than $1 million

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$10,000 to $99,999

National Aeronautics and Space Administration

OTHER

$10,000 to $99,999

American Cancer Society
Biosphere Two Center, Inc.
International Human Frontier Science Program



Carnegie Science Education: Becoming Part of the Story of Science

"When I examined myself and my methods of thought I came to the conclusion that the gift of fantasy meant more to me than my talent for absorbing positive knowledge."

Albert Einstein

As humans, we are the carriers of the knowledge and experience of the past. This truth shapes traditional science education, which is typically about past discoveries made by someone else. But as individuals, we are always making discoveries for ourselves. First Light and CASE (in their 12th and 6th years, respectively) seek to expand traditional science education by developing the capacity of both youngsters and grown-ups to make insightful discoveries about the world around them. By doing so, the students become a part of the story of science and experience firsthand its curiosity, discovery, and surprise.

Ironically, many schools insulate students against surprise—especially in science education. Educators craft textbooks, handouts, and work sheets so carefully that often there is nothing left to discover, no personal role for the student except to learn the story of what others have done. To be truly educated however, is to learn things for oneself.

In contrast, science education at Carnegie is an adventure celebrating the thoughts, products, and involvement of the students. We encourage pupils to ask questions and develop procedures for drawing their own conclusions. Where the traditional model skips to the end of the story, the Carnegie model stimulates students to become part of the story.

To learn the story of science requires, above all, a highly developed imagination. Perhaps more important than any concept we teach, is to spark the imagination and curiosity of students so that they want to take the questions of the past and explore them today.

The study of electricity provides an example. The traditional approach is to describe the discovery of electricity and the invention of the first electric devices. At Carnegie this is just the beginning. Students here participate in the phenomenon of electricity by harnessing its use through making and testing batteries, experimenting with resistance, and applying it to various problems.

Left: Weekly field trips at First Light often provide the materials for unique investigations. Here students learn how natural resources were used in everyday life.

Following in the Footsteps of Scientists

Because Carnegie has five research departments, students here have an added advantage: they can learn science by following in the footsteps of real scientists. One exciting new area under investigation involves ocean life. This topic was first covered at First Light over a decade ago. Students this year took a fresh look at the subject in conjunction with the institution's work in astrobiology. Astrobiology is a multidisciplinary field, carried out at Carnegie and elsewhere, to discover the origins and distribution of life in the universe. One component is to look at the evolution of ocean life. Over the next three years, the research conducted by Carnegie scientists will be translated into activities for youngsters and posted on a new Web site beginning in the spring of 2000. Students will explore the same fundamental questions the scientists will, such as how other biospheres can be recognized and how habitable worlds form and evolve.

Learning by Doing

To introduce the subject of ocean life to the students this year, we initiated a discussion on seawater and salinity. First, we asked them how we could measure the salt in salt water. A great idea emerged, which focused on evaporation: If you take a known quantity of water and evaporate it, you will be left with the salt, which can be weighed. The class did just that by creating varying concentrations of salt water, evaporating it, and weighing the remaining salt.



Weekly field trips, such as this one to the Patuxent River Park at Jug Bay in Maryland, often provide the materials for unique investigations. On this excursion, students learned how the Piscataway Indians used the land and resources to survive in the region.

Another topic that emerged has to do with density. The class noted that it is easier to float in seawater than in freshwater. To understand why this is so, we put an egg into a beaker of water and examined what happened to it as salt was added. Several youngsters thought that the salinity of seawater could be measured by observing how the egg was suspended in the water.

The students wanted to experiment with something else. We took a plastic pipette and filled the bulb portion with different kinds of materials: copper, steel, lead, and plastic shot. In essence, we created a crude but effective hydrometer for comparing densities. But we lacked a way to make measurements. One child observed, "It's like a thermometer without any numbers." We needed to devise a scale and a method for calibrating it. The class agreed to mark the hydrometer in millimeters with the baseline level set by water. We could then measure density changes from one experiment to another. What did the youngsters want to test with the new instrument? They immediately suggested different liquids—coke, oil, and alcohol. The class had developed the tools that paved the way for the true inquiry, and the questions they posed were many: Why were there differences among liquids? Did temperature change the results? Did mixing two liquids with known densities change the density of the new solution? Would sugar produce a liquid as dense as salt? As each new test was performed, a new act in the story of science unfolded. In two short hours, the class explored questions and experienced concepts related to investigative protocol, instrumentation, calibration, measurement, density, temperature, and fair testing. In that one class, the students lived a complete science story.

The Foundation for Inquiring Minds

Imagination, curiosity, and inquiry provide the most important foundations for studying science. Albert Einstein recognized this when he wrote, "When I

examined myself and my methods of thought I came to the conclusion that the gift of fantasy meant more to me than my talent for absorbing positive knowledge." Instilling these features into young minds creates safeguards so that our teaching does not become a dead-end; it also ensures that we will keep alive the wonder of science.

CASE Summer Science Institute

Every summer for the past six years teachers from Washington, D.C., public schools have participated in a CASE experiment: for six weeks we immerse them in a program, similar to the one used in First Light, of doing science. This experiment will tell us whether our approach to teaching science by doing science can change the way the subject is taught in the city's elementary school classrooms. The ultimate goal is for the D.C. students to learn to ask good scientific questions, investigate them, collect and analyze data, and present their results.

We have observed that children, both in First Light and in the city's classrooms, love to do science this way. We've seen how learning is sparked when they build structures out of straws and paper clips or observe the life cycles of butterflies, moths, and mealworms. This teaching technique provides the students with a variety of learning strategies and the means to show what they have absorbed. Their observations give them something to write about and a reason to read. Conducting measurements, integral to collecting and presenting data, also affords students an opportunity to use mathematics. The important skill of logical reasoning is strengthened because it is inherent in scientific investigation. Alva Abdussaalam, a CASE teacher at the special education center, Prospect Learning Center, says of our method, "It works!" She maintains that this way of teaching science allows her students to learn.

Sue White, the CASE mathematics coordinator, frequently observes that there are children who learn differently from other children. These students usually struggle in school and often fail academically because the teaching methods are not geared to the way their minds work. The kinds of



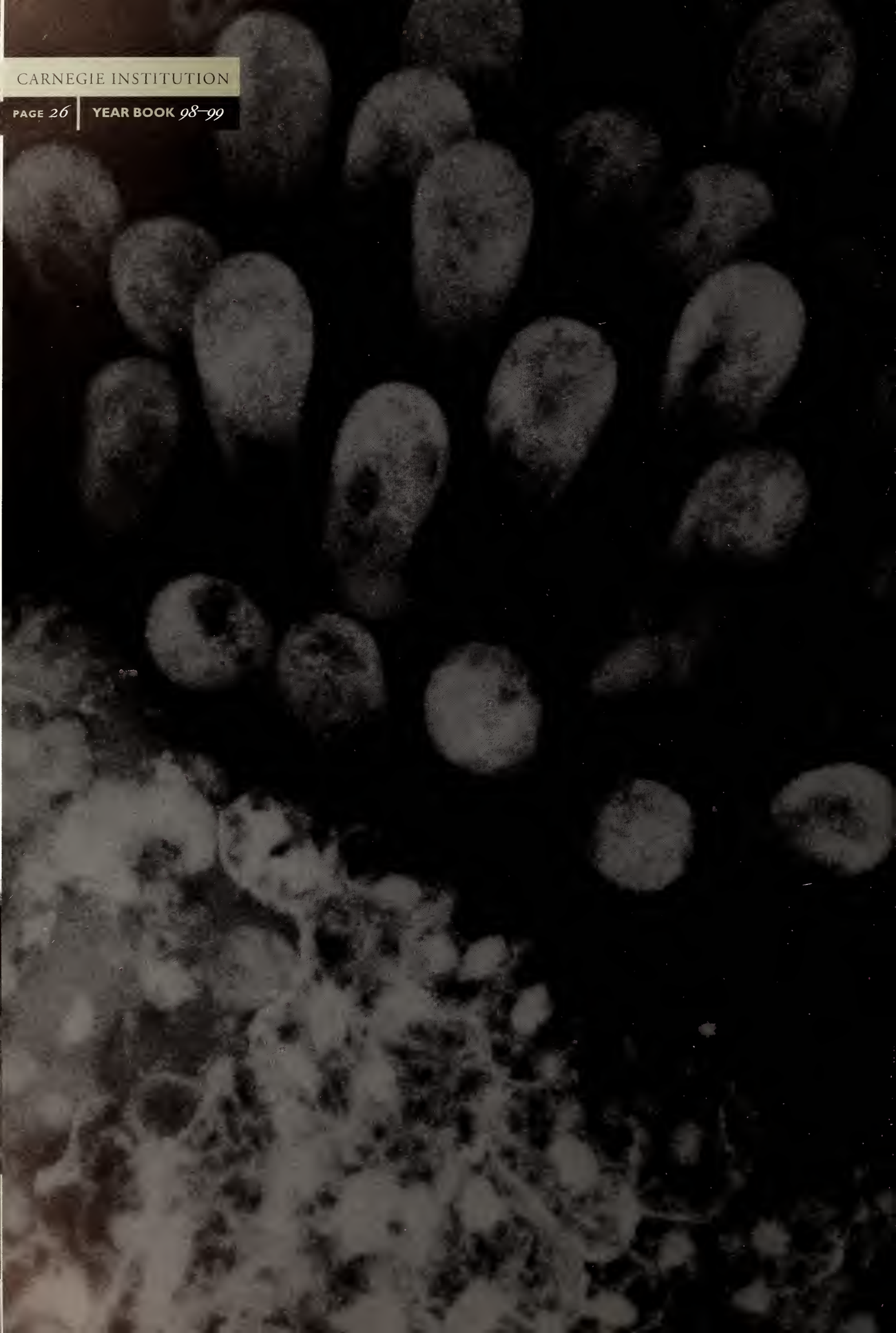
Charles Mercer, a CASE graduate and mentor teacher, achieved the highest honor a Washington, D.C., instructor can attain: Teacher of the Year. He is shown here with Carnegie president Maxine Singer at the awards ceremony in 1999. Mercer attributes much of his success and growth to the CASE program.

science activities that we have developed at CASE, and the teaching strategies that accompany them, do not rely exclusively on verbal and writing abilities for the expression of ideas. Perhaps these methods can be used to assess the learning potentials of these students and help them learn in a new way.

CASE Summer Mathematics Institute

For years, CASE teachers have asked us to run a summer institute in mathematics like the one in science. This past summer Sue White and Dr. Monica Neagoy from Georgetown University did just that. A small group of CASE teachers were invited to participate. They encountered fractals and chaos theory, mathematics concepts new to them; learned ways to prepare their students for algebraic thinking; and explored mathematical tools such as the graphing calculator. As the session progressed, they confirmed our ideas that professional development for teachers must be rich in content and taught in a variety of ways. These teachers also affirmed that our approach to strengthening the teaching of science and mathematics in the elementary classrooms of D.C. public schools is one that can improve the abilities of students today and in the future.

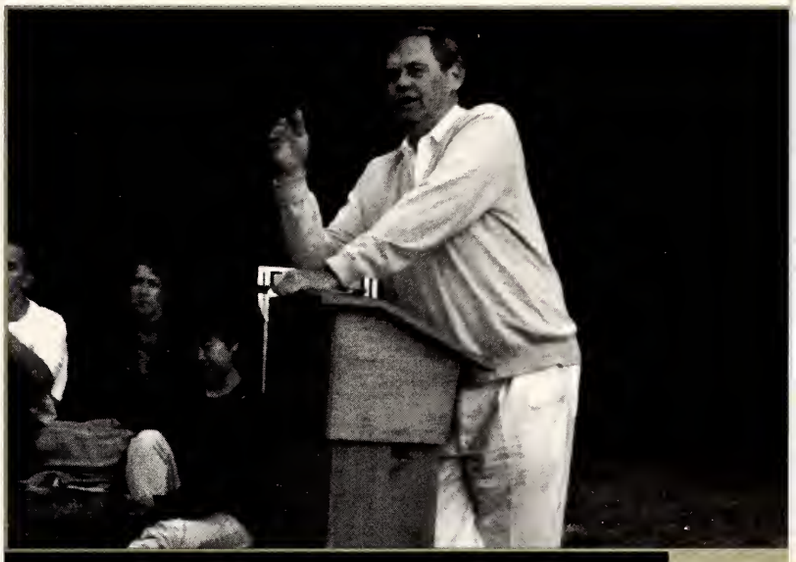
— Chuck James and Inés Cifuentes



THE DIRECTOR'S INTRODUCTION

The past year was a time of many changes for the department. In June 1999, Olle Björkman formally retired, more than 30 years after arriving at the department for a one-year postdoctoral appointment. At a dinner held in his honor, Olle commented that the Carnegie postdoctoral fellowship program had exceeded his expectations and should be continued at all costs. It is hard not to agree with his sentiments, and during the past five years I have made a major effort to redirect endowment spending away from departmental services and into fellowships. Although this has meant that the department provides fewer services, I believe that this disadvantage is more than offset by the effects of being able to support at least five postdoctoral fellows. I fervently hope that some of the fellowships will support people who have a fraction of the influence that Olle has had on plant biology. I look forward to seeing what retirement means for someone who has remained actively engaged at the bench throughout his career. I will note for the record that Olle is currently somewhere in the mangrove swamps of northern Australia pursuing his research interests in mangrove diversity.

Several other longtime members of the department also took their leave this year. Neil Hoffman left to assume a position at Paradigm Genetics in North Carolina. Neil is currently managing a biochemistry group in the company, which is a recent start-up focused on exploiting functional genomics in *Arabidopsis*. Brian Welsh, the manager of our workshop, retired to Bodega Bay after 13 years at the department. Aida Wells retired to explore her interests in writing community grants. The main building seems eerily quiet, and it remains to be seen how anyone will find out what is going on in the department without her. Finally, I regret to say that Rudy Warren, our grounds manager, died unexpectedly.



Olle Björkman at his retirement party.

Because of the staff changes during the past several years, the department currently has fewer Staff Members than is desirable. Therefore, during the coming year we will begin making new appointments. In anticipation of these changes, the president and the trustees provided about $2.8 million during the year for renovations to several of the buildings. The "main lab," where Art Grossman and Neil Hoffman were most recently housed, was completely renovated and expanded. This building now provides laboratory space for the groups headed by Shauna Somerville, Art Grossman, and me. A new building was erected on the northwest side of the lot and now houses the shop, storage, and growth chambers. The "400 building," which used to house the shop, was converted to modern

Left: The apex of the female reproductive structure in an *Arabidopsis* flower is covered with specialized finger-like cells called stigmatic papillae. These cells interact with pollen cells to initiate fertilization of the flower. This three-dimensional image of living stigmatic cells was created by expression of jellyfish green fluorescent protein, laser scanning confocal microscopy, and computer imaging techniques. (Image courtesy David Ehrhardt.)



Renovation of the main laboratory does not mean work stops at the department.

lab space. In all, the amount of useful lab space has been substantially improved and expanded.

One of the first consequences of the expanded space was that it became feasible to consider undertaking projects that require reasonably large groups of people. In collaboration with Pam Green and colleagues at Michigan State, Mike Sussman and colleagues at the University of Wisconsin, and Steve Dellaporta at Yale University, Shauna has established a laboratory devoted to producing DNA microarrays for use within the department and in the community at large. Their group was awarded almost $9 million for this and other aspects of the project from the National Science Foundation (NSF). The goal is to make DNA microarrays containing at least 12,000 *Arabidopsis* genes. The arrays can be used to measure the expression of each of the 12,000 genes in response to a wide variety of environmental and developmental conditions. It is hoped that this approach will facilitate the identification of genes that participate in various cellular processes and provide fresh insights into how the expression of different pathways is coordinated.

Arthur Grossman and a group of collaborators have also begun applying genomics methods to the alga *Chlamydomonas reinhardtii*. They received $3.3 million from NSF to develop a number of broadly useful genetic tools for the research community. These will include production of sequenced cDNA libraries, the development of DNA arrays, and the production of a high-density genetic map of cloned polymorphic DNA fragments. In conjunction with the powerful genetic methods now available for this organism, these genomics tools should greatly facilitate the analysis of plant gene function in *Chlamydomonas*.

More recently, we received more than $5 million from the NSF to develop a new database for information about *Arabidopsis*. The project, called TAIR (The *Arabidopsis thaliana* Information Resource) is a collaboration between Carnegie and the National Center for Genomic Resources (NCGR) in Santa Fe. NCGR is responsible for developing software and computer applications, and we are responsible for designing the information content of the database and, ultimately, for entering the data. Former Carnegie student Sue Rhee has returned to the department to lead the project; the Web page that describes TAIR is located at http://arabidopsis.org. Former postdoctoral associate Eva Huala has also returned to participate in the TAIR project as lead curator. In view of the fact that the *Arabidopsis* genome will be completely sequenced by the fall of the year 2000, I am certain that the TAIR project will provide an essential new resource to the scientific community. My expectation is that the TAIR group will also discover completely novel biological insights that can only be derived by having access to complete genome sequences and advanced computing tools.

The departmental Staff Members summarize some of the research highlights of the past year in the following short essays.

—Christopher Somerville

Reflections on Olle Björkman's Career

This year marks a major change at the Department of Plant Biology: Olle Björkman retired. Born in Sweden, Björkman earned the equivalent of the Ph.D. in genetics at the University of Uppsala in 1960. At the Carnegie Institution, with which he has been associated since 1964, he has worked with other Staff Members and an illustrious string of visitors. His investigations of physiological and molecular mechanisms of photosynthesis and associated processes explore how plants adapt to extremes of light and temperature and to drought and salinity. Björkman has been a central figure in the development of environmental plant biology for nearly four decades. Over his career, he has received many honors in recognition of his research and public service contributions. He is a member of the U.S. National Academy of Sciences, a fellow of the American Academy of Arts and Sciences, and a foreign member of the Australian Academy of Science. He has received the Linnaeus Prize, awarded by the Royal Swedish Physiographic Society, the Stephen Hales Award of the American Society of Plant Physiologists, and the Selby Award of the Australian Academy of Science. These honors only begin to reflect the esteem the scientific community has for Björkman and his work.

At the time that Björkman joined the department, the experimental taxonomy group of Jens Clausen, Malcolm Nobs and Bill Hiesey was just finishing up on an epic series of experiments that demonstrated the existence of ecological races, genetically distinct units within a species adapted to different habitats. At the same time, new technical approaches and new insights into the molecular mechanisms of photosynthesis and other key physiological processes of plants were developing at the department (particularly by fellow Staff Member David Fork, also recently retired) and elsewhere. Björkman seized the moment, producing a synthesis of the genetics, ecology, and plant physiology/biochemistry of plant adaptation. This new approach, which drew from several disciplines, illuminated the plant adaptation problem at different levels of organization. Under Björkman's leadership, progress in this new area was spectacular.



The Stanford-Carnegie mobile laboratory is shown at work in Death Valley, California. This self-contained lab was used to measure the physiological properties of plants growing in their native environments. During these experiments, temperatures reached 50°C. One of the native plants examined in this study had very high rates of photosynthesis, and these experiments showed that the plant actually preferred this heat.

Björkman took advantage of the long-term (but modest) funding and the shop facilities at the Carnegie labs to develop new equipment, which defined the state-of-the-art in environmental plant biology. Together with his Stanford University colleague Harold Mooney, for instance, he set up a mobile laboratory in the early 1970s. This instrument package was used to make sophisticated measurements on plants in their native environments. The mobile lab field campaigns examined plants native to such contrasting environments as Death Valley National Monument in the heat of summer and the shaded floor of the coastal redwood forests. These studies demonstrated dramatic adaptive characteristics of plants to extremes of temperature, drought, salinity, and shade. The picture above is from July 1970 and shows the mobile lab at work in Death Valley, California. A young Olle Björkman is shown (following page) at the controls inside the mobile lab during an experiment.

The collaboration with Mooney also initiated a fundamental change in the way the department operated. A Stanford University graduate student, Jim Ehleringer (now professor and past chairman of the Department of Biological Sciences at the University of Utah) conducted the research for his Ph.D. thesis under Björkman's direction. Soon many other students followed this path, and worked with Björkman and other Staff Members. A close integration of the academic program of Plant Biology with Stanford's biology department was eventually formalized when Winslow Briggs became Director in 1973. Since then, more than 30 graduate students have conducted the major part of their thesis research at Plant Biology.

Björkman forged other partnerships. During a sabbatical jaunt in 1971-1972 to Canberra, Australia, he opened the way for many collaborative studies between members of Plant Biology and Australian scientists at the Australian National University and the CSIRO in the ensuing years. This came to be known as the "Carnegie–Canberra connection." It is significant that nearly half the participants in a recent symposium honoring Björkman's retirement came from the continent down under.

Throughout his career, Björkman mentored many students, postdoctoral fellows, and sabbatical visitors. He is legendary for the attention he showered on the members of his research team. A consummate bench scientist, he never had a large research group. Rather, he worked most happily with small groups—often only one or two individuals. These research "adventures" were highly orchestrated and extended far beyond the normal scientific collaboration. It could also be said that Olle's co-workers experienced some of the best meals and drank some of the best wines of their lives in the Björkman home.

Olle's career is punctuated with many research milestones. In the late 1960s, he began a series of comparative studies of closely related plants genetically adapted to contrasting shaded and sunny habitats. His studies showed that these plants possessed suites of biochemical and morphological adaptations that prepared them to function more efficiently in their respective native environments. In the course of this research he discovered that a single factor, the quantity of an enzyme RuBP carboxylase, determines the rate of photosynthesis at high irradiance. He also discovered and characterized photorespiration, C_4 photosynthesis, and photoinhibition, processes that have figured prominently in the rapid expansion of research on plant adaptation and physiological ecology. Collaborators who participated in making these advances include fellow Staff Members and visitors, Barry Osmond, Jan Anderson, Merv Ludlow, John Boynton, Bob Pearcy, and Eckard Ghaul.

In the mid 1970s, Björkman and Mooney initiated work that examined the potential range of thermal adaptation among higher plants and characterized the biochemical mechanisms that plants use to modify their thermal limits. Prominent participants in these studies include Paul Armond, Murray Badger, Merv Ludlow, Norio Murata, Gunnar Öquist, John Troughton and CIW technican Frank Nicholson.



Here, Olle Björkman is at work inside the mobile laboratory.

At his retirement symposium Björkman, Chris Niyogi, and Arthur Grossman presented another landmark achievement. His team used powerful new genetic approaches with the model organisms *Chlamydomonas reinhardtii* and *Arabidopsis thaliana* to establish that certain carotenoid pigments play an essential role in reversibly modifying the properties of photosynthetic reaction centers exposed to excessive light. The genetic elucidation of this mechanism was certainly the highlight of the symposium and, indeed, is one of the key findings in environmental plant biology of this decade. Björkman and collaborators Barry Osmond, Barbara Demmig, Steve Powles, Christain Schaefer, Crista Chrichley, Catharina Lindley, and longtime technician Connie Chu played key roles in characterizing this mechanism that plants use to cope with the stress of too much light.

Many of Björkman's former research collaborators attended the symposium held in his honor at a hilltop retreat in the Napa Valley region of northern California. Good food, good wines, and intensive scientific discussion were in abundance. Several former collaborators expressed the sentiment that they did the best work of their careers and felt the most important during their time of working with Olle. The symposium also offered an opportunity to reflect on the tremendous creativity and rapid progress associated with the early years of Björkman's career. Factors such as fortuitous timing, the audacity of youth, the availability of long-term stable funding, and a generous fellowship program certainly contributed to his dramatic success. But at the core, it was Björkman's intellect, curiosity, and intensity that led to breakthrough after breakthrough.

—*Joe Berry*

JOSEPH BERRY

Understanding the Global Carbon Budget

The year-to-year increase in the CO_2 concentration of the atmosphere is largely driven by combustion of fossil fuels and deforestation. However, natural processes such as exchange of CO_2 with the ocean, growth of plants (driven by photosynthesis), respiration of living organisms, and decomposition also play a key role. These processes, which constitute the Earth's carbon cycle, account for about 95% of the total exchange of CO_2 with the atmosphere. In preindustrial times, the global carbon cycle was balanced and the CO_2 concentration of the atmosphere was stable. At present, approximately two-thirds of the CO_2 added to the atmosphere by human activities is sequestered by these natural processes—presumably as bicarbonate in the ocean, wood in the forests, and organic matter in the soil. The remaining one-third accumulates in the atmosphere, perturbing the radiative properties of the atmosphere and possibly altering the climate. CO_2 sequestration by the global carbon cycle is, therefore, a major factor mitigating the potential impact of human activity on climate. The future course of anthropogenic climate change depends in no small part on how these natural components of the Earth's carbon cycle respond in the future. A great deal of effort is now focused on understanding where the carbon is going and in establishing a system that will permit us to monitor the dynamics of carbon cycling by the oceans and terrestrial ecosystems of the world.

The most powerful approach developed to date is based on a "top-down" analysis of the dynamics of CO_2 and other tracers in the atmosphere. Flask samples of air are collected at frequent intervals at stations located around the globe and sent to central laboratories operated by NOAA, Scripps Institution of Oceanography, and CSIRO. Analyses of these samples, for O_2 and CO_2 concentrations and other trace gases, provide important constraints on inversion calculations that attempt to determine the net uptake or release of CO_2 from surface reservoirs and to locate these



Joe Berry (right) in the field.

sources and sinks. One of the key measurements is the ^{13}C and ^{18}O isotopes of CO_2. Great care is taken in the measurement protocols used to analyze the flasks so that the isotopic measurements are of the highest possible accuracy and to provide standards so that measurements conducted at different times or in different labs are comparable. However, these methods require large samples of air (typically 2 liters), and the measurements are labor intensive.

It is widely recognized that these global measurements need to be supplemented by process-level studies of isotopic effects at the regional, ecosystem and plant scales. Such data is needed to calibrate and test the models of isotopic fractionation used to interpret the global observations. Work at these scales needs to be conducted with a precision similar to that of the global-scale networks; even a modest level of experimentation could easily generate as many samples as are now processed by the global sampling programs. While the managers of these global programs are sympathetic to the need for local-scale measurements, they simply do not have the capacity to fill this need. Ecosystem scientists have been reluctant to make the large commitments of laboratory space, equipment, and personnel to duplicate these facilities.

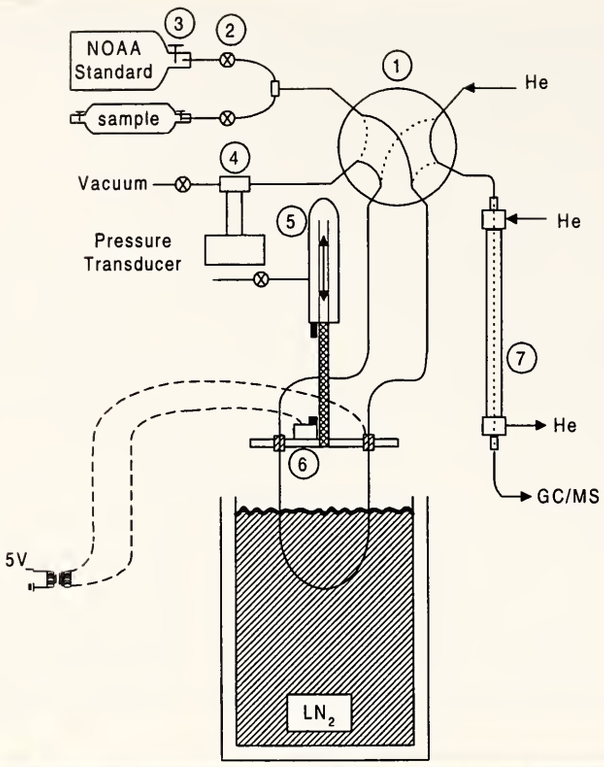


Fig. 1. A two-position-six port Valco valve (1) is used to switch the connections between a "trapping state," with the capillary connecting the sample or standard flask to the vacuum chamber, and a "CO_2 release state," with the helium flow directed through the trapping capillary and on the mass spectrometer. An air-actuated plunger (5) is used to submerge or withdraw the trapping capillary in a liquid nitrogen dewar.

With the six-port valve in the trapping state, air is permitted to bleed through the trap and into the vacuum chamber. During this time the valve diverts the flow of helium directly to the mass spectrometer. Pneumatically activated microvalves (2) provide on/off control on the flow of air from either the sample or the standard flasks. The quantity of air sampled is measured manometrically with a high-precision capacitance manometer (0-100 mbar). Once a preselected quantity of air is admitted, the inlet valve is closed, the pressure is measured, and the residual air in the system is pumped away. The six-port valve is then switched to the release state. The trap is withdrawn from the dewar, and a microswitch is tripped, permitting a current to flow through the stainless steel capillary. This current heats the capillary to about 80°C, quickly volatilizing all of the CO_2 and water that had been trapped. A nafion drier (7) downstream of the trap removes the water and a capillary gas chromatography column separates the CO_2 from the N_2O before the gas reaches the mass spectrometer. By alternately sampling air from the sample flask and one containing a standard, both the CO_2 concentration and the isotope ratio of the sample can be referenced to other measurements. The CO_2 concentration is determined to a precision of 0.5 ppm and the isotope ratios are determined to a precision of 0.05 parts per mille.

All of the valves can be computer controlled, permitting the process to be automated. Each cycle of trapping and release typically takes about four minutes. A typical measurement sequence consists of 10 cycles, 5 each of the sample and a flask containing a standard air. A multiposition valve (not shown) can be used to permit analysis of several sample flasks overnight.

This report describes a new technology for measurements of CO_2 concentration and isotopic composition of CO_2 in air samples. This technology is specifically intended for ecosystem and plant or leaf-scale measurements. Significantly, the technology uses very small samples of air (less than 5 ml for a complete analysis) while achieving levels of accuracy and cross-calibration that approach those of the flask networks. Most important, the procedure can be automated. In this new method, the batch inlet system of a conventional isotope ratio mass spectrometer is replaced with a continuous flowing helium inlet system. Samples are introduced as plugs in the flow of helium, and the isotope ratio is calculated from measurement of the "peaks" at m/e 44, 45, and 46 that are recorded when a sample of CO_2 passes through the mass spectrometer source. Typically, the quantity of the sample required for a measurement with the flowing helium inlet is about 10^5 that required for a measurement with a batch inlet system. The system described here functions to isolate the CO_2 from a given quantity of air and to release that CO_2 into a stream of helium that carries the sample into the mass spectrometer. Additionally, by measuring the amount of air used and the size of the CO_2 peak, one can calculate the CO_2 concentration in a sample.

A schematic diagram of the system is shown in Fig. 1. Air containing CO_2 is withdrawn from a flask and flows into an evacuated volume through a capillary tube immersed in liquid nitrogen. CO_2 is quantitatively trapped from the air, and it is rapidly released when the trap is withdrawn from the liquid nitrogen.

WINSLOW R. BRIGGS

Identification and Characterization of the Photoreceptor for Phototropism in Higher Plants

Briggs and collaborators previously demonstrated that the protein encoded by the *NPH1* gene in *Arabidopsis* was a classic serine/threonine kinase, and that blue light activated its autophosphorylation both in vivo and in vitro. Physiological studies and studies with mutants at the *nph1* locus conclu-



Director Emeritus Winslow Briggs

sively demonstrated that the nph1 protein was essential for all of the phototropic responses known in *Arabidopsis*, including the negative phototropism of the roots. The researchers did not know, however, whether the protein was also the photoreceptor for the light-activated phosphorylation and hence the photoreceptor for phototropism, or whether it was activated by a separate photoreceptor. The answer came when postdoctoral associate John Christie successfully expressed the *NPH1* gene in an insect cell/virus system. His experiment showed that if the insect cells were kept in the dark while they were expressing the gene and the proteins were subsequently isolated under a dim red safelight, the recombinant protein retained its photosensitivity. Not only did blue light activate its phosphorylation, but the time course for phosphorylation and the fluence dependence were both virtually identical to those of the native protein. Since no other plant protein was present in the preparation, and since insect cells expressing the protein accumulated large quantities of flavin mononucleotide (FMN), the researchers concluded that Nph1 was indeed its own photoreceptor, and that its light-sensing chromophore was FMN. The absorption spectrum for the chromoprotein was virtually identical to the action spectrum for phototropism, leading the scientists to conclude that they had finally begun to characterize the photoreceptor for phototropism. The collaborators named the protein phototropin.

An interesting characteristic of phototropin is that it has two domains, each about 40% identical to the other, which are also found in a wide range of proteins involved in signaling. These proteins all respond to either Light, Oxygen, or Voltage, so the scientists designated the regions of amino acid similarity LOV domains. The proteins bearing LOV domains have been reported in organisms ranging from the most primitive bacteria through mammals. Two that have been characterized at the protein level are both known to be flavoproteins. Since the only element that these proteins shared with Nph1 was a LOV domain, the scientists hypothesized that the LOV domains might be the specific sites that bound FMN. It was possible to express either single LOV domains or a construct encoding both LOV domains in *Escherichia coli* and purify the recombinant polypeptide nearly to homogeneity. The products were water soluble and bound FMN stoichiometrically: constructs expressing a single LOV domain showed a FMN:protein ratio of 1.0, while those expressing constructs with two LOV domains showed a ratio near 2.0. Phototropin, therefore, proved to be a dual chromophore photoreceptor.

Recently, the researchers found that LOV domains undergo photobleaching that is fully reversible in subsequent darkness. The spectral change is consistent with the formation of a covalent bond between the sulfur of a cysteine and one of the carbons of the FMN. Indeed, when the only cysteine in one of the LOV domains is mutated to a serine, the absorption spectrum of the FMN/polypeptide construct is the same as in the wild-type spectrum. This indicates normal FMN binding, except that the photobleaching is entirely eliminated. Other optical studies indicate a fairly major protein conformational change in one of the FMN/polypeptide constructs with blue-light irradiation—a change that is also eliminated when the cysteine is mutated to a serine.

In a related project involving contributions by Margaret Olney, John Christie, Gerard Lacève, Juliette Leymarie, and Alain Vavasseur, the scientists obtained evidence that *Arabidopsis* contains at least four blue-light receptors. Several of these photoreceptors have been described for higher

plants in the past few years, and in a couple of cases, hypothesized to play a role in phototropism. These include cryptochromes 1 and 2 and a system utilizing zeaxanthin as its chromophore. The researchers obtained null mutants for the two cryptochromes and a mutant unable to synthesize zeaxanthin, and tested their phototropic sensitivity and their capacity to undergo blue-light-induced autophosphorylation of phototropin. In all cases, including cryptochrome 1-cryptochrome 2 double mutants, phototropism was normal, as was light-activated phosphorylation. The collaborators concluded that none of the photoreceptor systems could play a direct role in detecting the direction of unilateral light and mediating the consequent development of phototropic curvature. The zeaxanthin mutant was known to lack the normal blue-light-induced opening of its stomata, and the researchers tested both the two cryptochrome mutants and a phototropin null mutant for stomatal opening to determine whether any of these photoreceptors played a role in the stomatal response. In all three cases, the blue-light-induced stomatal opening was normal. These results indicate that *Arabidopsis* has a minimum of four blue-light photoreceptors: phototropin, the two cryptochromes, and a photoreceptor mediating blue-light-induced stomatal opening.

David Ehrhardt
Mechanisms and Roles of Intercellular Interactions

Higher plants are remarkably organized collections of individual cells. All multicellular organisms share the common problem of how to create multicellular diversity and form beginning from a single cell. To accomplish this task, the processes by which cells divide, grow, and acquire new identities and functions must be coordinated with the activities and identities of other cells. Short-range interactions among cells have been shown to play key roles in establishing cellular identity, patterns of cell morphogenesis, and multicellular pattern formation. However, little is known about the machinery by which plant cells perform these interactions, how this machinery is assembled and regulated, and how cell-cell interaction affects subcellular organization and morphogenesis. Researchers in the Ehrhardt lab are pursuing the problem of cell-cell interaction and its role in cellular and multicellular development in the model plant *Arabidopsis thaliana*. The scientists are taking a multidisciplinary approach—including genetics, protein engineering, and confocal microscopy—with an emphasis on observation and manipulation of live cells and their components.

The ability to introduce the jellyfish green fluorescent protein (GFP) into cells of other organisms as an expressed genetic sequence is enabling new experimental approaches to cell and developmental biology. The Ehrhardt lab is exploiting GFP to create new tools for visualization of plant cell structure and behavior, and to identify genes of functional interest. For example, many proteins that are involved in cell-cell and cell-wall interaction are expected to localize to the cell periphery, or to domains about the cell periphery. Use of GFP, combined with the ease with which *Arabidopsis* can be transformed, has made it possible for the researchers to design and conduct large-scale screens for genetic information that confers specific subcellular localization properties. In a collaborative project with Sean Cutler, a GFP::cDNA fusion library was created and transformed en mass into *Arabidopsis*. Individual transgenic seedlings were screened for GFP localization patterns with confocal microscopy. This screen identified a large number of genetic tags that confer distinct subcellular localization patterns to GFP. Among the variety of tags that were recovered is a marker that localizes to the cell periphery and accumulates in discrete foci at cell-cell contact sites, structures that are likely to be the cell-cell channels known as plasmodesmata.

Plasmodesmata are the only points where most plant cells come into direct contact with each other without an intervening cell wall, and are hypothesized to play important roles in cell-cell interaction, including the possible exchange of informational macromolecules involved in development. Very little is known about the components that make up plasmodesmata, the genes that encode the components, how the plasmodesmata are assembled at particular cell junctions, or how

communication through them may be regulated. The researchers hope to exploit the new GFP tag as an entry point to pursue these questions.

Confocal imaging of GFP is proving to be a robust method for visualizing cell behavior, including behavior related to morphogenesis. The group is employing their collection of GFP markers to study the mechanism of cytokinesis in *Arabidopsis* shoot cells. Plant cells divide very differently from animal cells. A new cell partition, a phragmoplast, is initiated as an internally assembled structure before it is fused to the parental cell membrane. It is during phragmoplast development that some plasmodesmal channels are initiated. Confocal imaging of GFP is opening a new window on cell division by giving researchers the ability to visualize three-dimensional aspects of cytokinesis as it occurs in living cells. This technique provides access to cells that were previously difficult to observe, such as those in the shoot epidermis and cortex, permitting the researchers to address questions about how these cells perform cytokinesis in their native multicellular context. In addition, the variety of GFP markers that the group has isolated allows them to extend questions about cytokinensis to the behavior of discrete organelles and cell compartments.

Important patterns of cell-cell interaction are established during embryogenesis. However, the *Arabidopsis* embryo has been challenging to study as a living system. Using their GFP tools, the Ehrhardt group is developing methods to image live embryos. The methods have allowed the researchers to obtain three-dimensional images of the entire cellular structure of live early embryos. These techniques will expand and make it possible to define in new ways the cellular phenotypes of mutations that affect the development of the embryo and possible plasmodesmal mutants that they hope to acquire with use of the GFP marker.

A greater understanding of plant development will give biologists insight into the diverse mechanisms that have evolved to solve the problem of multicellular life. This information may one day help scientists engineer crop plants that make more efficient use of limited resources and are better optimized to produce food and novel products.

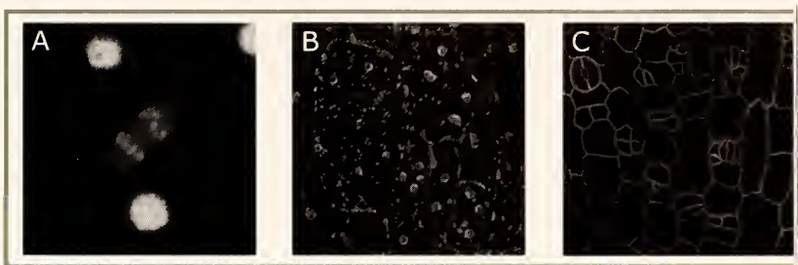


Fig. 2. A variety of subcellular markers are isolated by screening an expression library of GFP::cDNA fusion proteins in *Arabidopsis*. (A) A fusion to the carboxy terminus of CRY2 accumulates in the cell nucleus and is associated with condensed chromosomes during mitosis. Shown is a single confocal section of a root cell in anaphase of mitosis, surrounded by cells that are in interphase. CRY2 is a blue-light photoreceptor that affects a variety of plant developmental responses to light. (B) The library screening method is capable of yielding surprises. This panel shows a computer reconstruction of hypocotyl cells expressing a fusion to a novel protein. This protein accumulates on the surface of an organelle that remains to be positively identified. (C) This is a computer reconstruction of young leaf epidermis. These cells express a fusion protein that localizes to the plasma membrane. Imaging of plasma membrane markers allows clear visualization of epidermal cell pattern. A mature pair of guard cells forming a stomate is shown in the upper left. Cell division patterns leading to stomatal development are clearly visualized visible throughout the image.

Chris Field
Simulating Global Climate Change

In 1998 the Field lab, in collaboration with Harold Mooney and his group at Stanford, launched a major new global change study, designed to look at four of the main ways the global environment is changing. The study is a manipulative experiment in which grassland ecosystems are exposed to four different components of global change: elevated CO_2, warming, increased water inputs, and nitrogen deposition. The treatments include two levels of each of the factors (enhanced versus ambient) and all possible combinations of the four factors, for a total of 16 treatments.

Three main questions motivate the design. First, the scientists want to know when effects of global change factors are additive. This is important because most experiments address the global change factors individually, and there is a risk of misinterpretation if the factors interact in unexpected ways. Second, they are asking how much of the ecosystem response comes from changes in the composition of the community of plants, microbes, and animals in

the plots, versus changes in the physiology, biochemistry, and morphology of species present at the beginning of the experiment. Most experiments run for a time period that is shorter than the longevity of the dominant plants, and therefore have limited access to the components of the response driven through changes in species composition. Third, the researchers want to identify the pathways through which each of the global change factors affects primary production, carbon storage, nutrient dynamics, the water budget, and species composition. One of the most interesting aspects of global change effects on ecosystems is that the responses are rarely direct. It is not uncommon for an ecosystem response of interest to be separated from the direct response by three or even more layers of indirect responses.

The experiments are located on Stanford University's Jasper Ridge Biological Preserve, in an area dominated by annual grasses. The treated plots are relatively small, but the small size and high density of the plants means that even a plot of 0.8 m^2 has several thousand individuals of the dominant species—certainly enough to qualify as a whole ecosystem. Because the researchers placed a priority on keeping the conditions as natural as possible, they are using chamberless methods to apply all of the treatments. The warming is from overhead infrared lamps (designed to warm chicks), and the CO_2 is released as a cloud over each treatment plot. The CO_2 release rate is controlled by a computer to rise and fall with the wind speed, keeping the concentration (approximately twice that in the current atmosphere) over each plot relatively constant.

The treatments with added water and added nitrogen fertilizer do double duty in this experiment. First, they mimic important global changes: many of the world's ecosystems are already heavily impacted by nitrogen deposition, and climate models almost universally predict that precipitation increases in parallel with temperature. Second, the water and nitrogen treatments provide probes for untangling the direct and indirect effects of the CO_2 and warming treatments. For example, CO_2 can increase plant growth directly by increasing photosynthesis, but it can also act indirectly by decreasing stomatal conductance and increasing soil moisture. Similarly, warming can accelerate the decomposition of soil organic matter through metabolic stimulation of the soil microorganisms; it can also have the opposite effect by drying the soil.

The experiment is a useful approach to studying global change because the changes really are occurring in combination and over a long enough period to encompass several generations of many species. Some aspects of a deliberate manipulation are always unnatural (for example, the sudden imposition of the experimental treatments). But careful assessment with models can help isolate the nonnatural effects of the treatments. By examining a broad range of processes in an ecosystem with substantial functional diversity, the scientists hope to uncover general principles that will help predict global change responses in all ecosystems.

The first growing season with the experiment operating is now complete. The preliminary analysis points to some patterns that the researchers expected and some they did not. Among the expected responses was the earlier flowering of grasses in the heated treatments. However, the grasses grew the largest in the treatments with both added water and added nutrients. Elevated CO_2 had one potentially important unexpected response—it enhanced the success of shrub seedlings, suggesting that it could play a role in transforming the grassland to shrubland. So far, most of the significant responses are in the one-factor and two-factor treatments, rather than in those with three or four factors.

A number of recent studies with simulation models highlight the difficulty of interpreting long-term ecosystem responses from short-term experiments. To provide enhanced resolution on the dynamics of the processes with long time constants, the scientists are using ^{13}C, ^{14}C, and ^{15}N to trace the movement of carbon and nitrogen into pools of soil organic matter with a range of turnover times. The most valuable insights on the long-term dynamics of species composition, carbon storage, and other processes will come from the combination of the tracer analysis and several years of experimental treatments.

ARTHUR R. GROSSMAN

Regulation of Phosphorus Limitation Responses in *Chlamydomonas*

Agricultural soils typically contain suboptimal levels of phosphate (Pi). Consequently, Pi is an important component of supplementary fertilizers. Usually some of this supplementary Pi is lost from agricultural fields as runoff into nearby lakes and rivers, which can lead to algal blooms, eutrophication of aquatic ecosystems, and fish kills. The sustainability of agricultural yields and the quality of aquatic ecosystems depend on more efficient acquisition and use of Pi by crop plants. Efficient Pi utilization by plants will also decrease our dependence on rock phosphate reserves, a commodity that is often mined with negative economic and ecological consequences.

Researchers in Grossman's lab are interested in understanding the mechanisms that regulate phosphate metabolism in plants. Some of their recent work has focused on phosphorus starvation responses. In several organisms, phosphorus starvation responses include the induction of proteins that allow the cells to acquire Pi more efficiently (such as alkaline phosphatases with broad substrate specificities and high-affinity Pi transporters) and the slowing, or cessation, of cell division. A two-component regulatory system (PhoB and PhoR) governs responses of *Escherichia coli* to phosphorus limitation. In *Saccharomyces cerevisiae*, phosphorus starvation responses are controlled by a cyclin-dependent kinase (Pho80-85) complex. Wykoff, Usuda, Shimogawara, and Grossman recently characterized phosphorus starvation responses in the unicellular green alga *Chlamydomonas reinhardtii* and screened for mutants that were unable to accumulate extracellular alkaline phosphatase in response to phosphorus limitation. One of the mutants obtained, designated *psr1* (phosphate starvation response), is unable to induce specific responses to phosphorus starvation, including the accumulation of high-affinity Pi uptake and the secretion of alkaline phosphatases. Further characterization of the mutant demonstrated that although wild-type cells continue to divide three to four times upon the imposition of phosphorus starvation, the *psr1* mutant stopped dividing almost immediately. The mutant appears to be unable to access external and/or internal reserves of Pi and consequently is unable to continue dividing. Wykoff and collaborators cloned the *PSR1* locus to better understand how phosphorus starvation is regulated and to determine the relationships among regulatory systems that govern Pi metabolism in photosynthetic and nonphotosynthetic eukaryotes.

The *Psr1* gene encodes a protein of 762 amino acids. Although the entire length of the protein is not similar to polypeptides represented in the database, the protein does contain numerous small regions that resemble specific domains of transcription factors. Most striking is a 59 amino acid region (amino acids 187 to 245) that is similar to a domain of Cca1, a transcription factor in *Arabidopsis* that regulates light-harvesting genes in response to circadian rhythm. This region is required to bind Cca1 to DNA in a sequence-specific manner and is postulated to be a distantly related myb DNA binding domain. Myb domains have been shown to mediate various types of transcription, and thus, Psr1 could be a transcriptional regulator. *Arabidopsis* also contains a second gene (represented in the EST database) encoding a protein with strong similarity to Psr1 in the "myb-like" domain. Psr1 also has three glutamine-rich tracts; these regions are present in certain transcription factors and appear to be involved in the activation of gene expression. Another feature of Psr1 is a serine/threonine-rich region and a possible metal-binding site.

To monitor the level of Psr1 and determine its subcellular location, a hemagglutinin (HA) peptide epitope tag was incorporated into the protein. Strains harboring the epitope-tagged Psr1 were stained with a red fluorescent dye specific for DNA and a green fluorescent immunochemical staining system, which allows the tagged Psr1 protein to be visualized. The stained cells were viewed by confocal microscopy after exposure to various environmental conditions (Fig. 3). The intense red fluorescence (light gray) defines the nucleus of the cells in the image (1). Cells from nutrient-replete cultures exhibited a low level of green fluorescence in the nucleus with little in the cytoplasm. After 24 hours of phosphorus starvation, the nuclei fluoresce

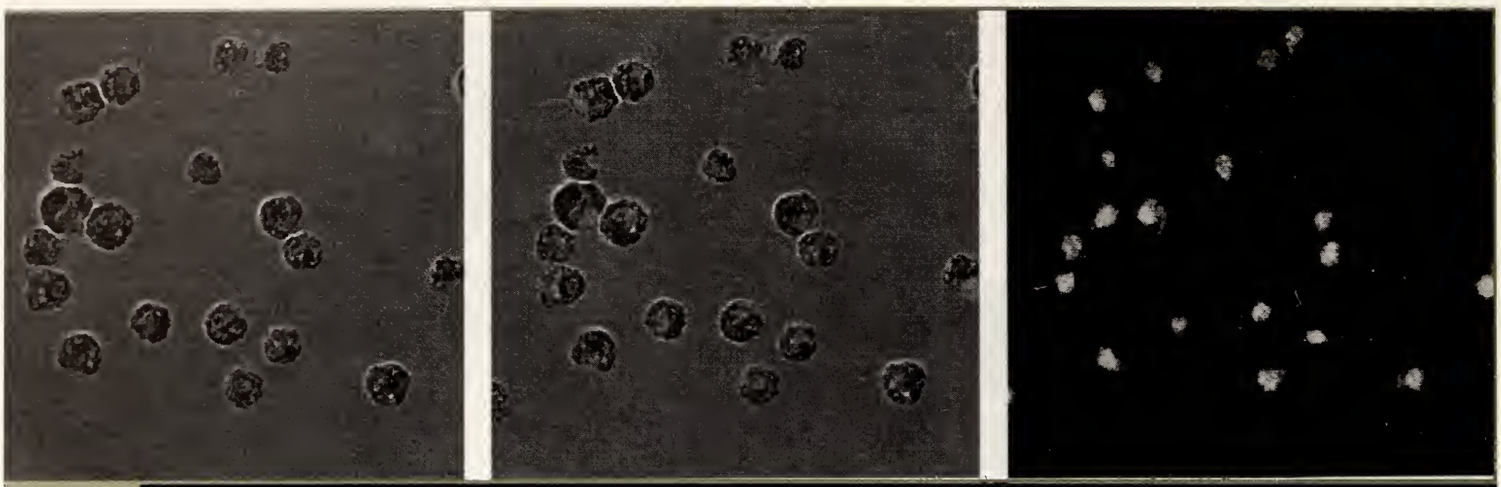


Fig. 3. This series of images shows the Grossman's lab test for monitoring the Psr1 protein's levels and locations within cells.

bright green (light gray, 2). Overlap of immunolocalized Psr1 with the nuclei is represented as yellow fluorescence (glowing areas, 3). Together the results demonstrate that Psr1 is a phosphorus-starvation-inducible, nuclear-localized protein. Since approximately the same amount of fluorescence is observed in the cytoplasm of *Chlamydomonas* cells, whether or not they are starved of Pi, Psr1 localization to the nucleus is not likely to be the key regulatory step in controlling the phosphorus starvation responses. Finally, the scientists examined the expression of the *Psr1* transcript during phosphorus replete and phosphorus starvation conditions and observed that transcript levels increased approximately tenfold after 12 hours of starvation; they began to decline soon after.

Psr1 regulates only some responses of *Chlamydomonas* to phosphorus starvation. The mutant cells still survived prolonged phosphorus starvation, and photosynthesis was down-regulated during phosphorus deprivation of the *psr1* mutant. These results indicate that other regulatory factors influence phosphorus starvation responses. Psr1 is the first regulator of Pi metabolism identified in a plant. Significantly, it has similarity to *Arabidopsis* sequences, suggesting that Pi metabolism may be similarly regulated in vascular plants. It is interesting that Psr1 does not resemble any genes in *Saccharomyces*; this raises the possibility that Pi metabolism in *Chlamydomonas*, and possibly vascular plants, is regulated in a way that is different from that of nonphotosynthetic eukaryotes. Furthermore, Psr1 is induced during Pi starvation, differing from elements involved in controlling Pi metabolism in yeast.

The researchers propose a speculative but plausible model for Psr1 control of the phosphorus starvation responses in *Chlamydomonas*. The intracellular level of Psr1 is low at all times, with the majority of protein in the nucleus. During phosphorus starvation, the nuclear-localized protein is activated by an undefined mechanism and binds specific "Pi-sensitive" promoters. The genes that are activated early in the phosphorus starvation responses, such as that of the Pi transporter and the *Psr1* gene itself, may have a high affinity for Psr1. As Psr1 continues to accumulate, the lower-affinity promoters begin to bind Psr1; this could explain the lag in phosphatase induction relative to Pi transport activity. As the cells stop dividing and enter a quiescent phase, the transcriptional apparatus operates at a minimal level, and many genes, including those involved in the initial phases of the cell's responses to phosphorus limitation, become inactive. The group hopes to test these possibilities over the next few years.

Christopher Somerville
Genetic Dissection of Cell Wall Structure and Function

The plant cell wall is a complex structure composed of a variety of branched and unbranched high-molecular-weight polysaccharides and a variety of structural and catalytic proteins. Some cell walls also

contain lignin, a very high molecular weight polyphenol. Understanding the structure and function of plant cell walls is of interest for several reasons. First, because the wall controls cellular expansion, it seems likely that morphogenesis involves mechanisms that determine the direction and extent of wall expansion. Thus, understanding how the wall is made and modified may lead to insights into how plants control their body plan. Cell walls are also the major component of terrestrial biomass and are used in large amounts as sources of fiber (e.g., paper, cotton, fuel, and feed). Somerville considers it likely that if researchers understand the factors that regulate wall assembly it will be possible to greatly enhance the efficiency for using cell walls from agricultural and forestry species.

Relatively little is known about how cell walls are assembled or what the functional significance is of the various components. One reason for the limited progress is that it has been difficult to separate the components of the wall without altering them so that they no longer resemble their in vivo condition. A second reason is that most of the enzymes involved in wall synthesis have proved difficult or impossible to purify and characterize. Thus, the details of how the wall is made are sketchy. There is also no system that permits reconstitution of walls from purified components. Thus, it is not possible to examine how varying the components affects the physical properties of reconstituted walls. Indeed, there are numerous technical problems associated with the complexity of the structure and the high molecular weight and aqueous insolubility of the components.

One project in the Chris Somerville lab is focused on using genetics to try to dissect the function of the various components and to identify the enzymes that participate in wall synthesis. The basic idea is that since researchers cannot reconstruct walls of differing composition in vitro, it should be possible to do this in vivo by altering the activity of the genes that encode the various components. Several years ago Simon Turner, then a postdoctoral associate, initiated the isolation of a series of mutants with altered cell wall composition by screening for alterations in morphology of the vascular tissues in stem sections (Fig. 4). Among other things, the scientists identified four mutants *(irx1...4)* in which xylem cells collapsed because of deficiencies in the secondary cell wall. More recently, the Somerville lab in collaboration with Simon Turner's group at the University of Manchester, cloned one of the genes, corresponding to the *irx3* mutation, by map-based cloning.[1] This gene is closely related to a putative cellulose synthase gene cloned from cotton by Debbie Delmer and colleagues and is, therefore, thought to be a xylem-specific cellulose synthase. The analysis suggests that the *irx1* and *irx2* loci may define other components of the cellulose synthase complex and are, therefore, targets for map-based cloning.

In addition to the use of forward genetics, the group is exploring the use of functional genomics approaches[2] to try to identify other genes that participate in wall synthesis. The scientists are engaged in the analysis of the function of a large family of genes in *Arabidopsis* that show homology to cellulose synthase. To date, they have identified 44 members of this family in the database of public *Arabidopsis* sequences. The relationship of these

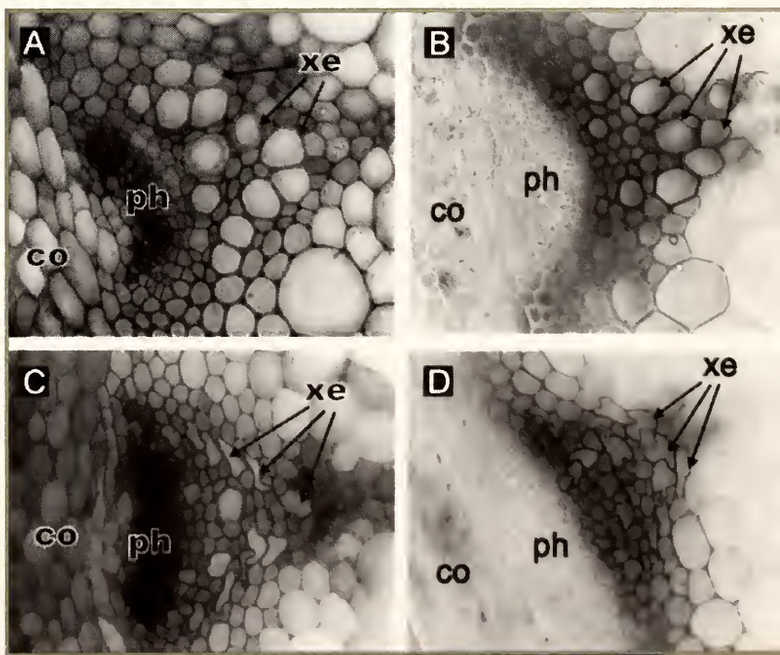


Fig. 4. This is a microscopic image of a transverse section through part of an *Arabidopsis* stem showing the phloem (ph), xylem (xe), and part of the cortex (co). In the *irx3* mutant (C, D) the xylem cells are collapsed because the secondary cell walls lack cellulose.

1 Taylor et al., 1999.
2 Somerville and Somerville, 1999.

genes to one another is shown on the Web site at http://cellwall.stanford.edu.

There are six major branches to the family of cellulose-synthase-like genes called CesA, Csl α, β, γ, δ, ϵ. The CesA branch contains *irx3* and other genes that appear to be cellulose synthases. The hypothesis is that the Csl genes represent the processive β-glycan synthases that make the β-linked polymers other than cellulose (i.e., cellulose is β-1,4-glucose). The researchers are exploring the function of the Csl families by making mutations in many of the genes, and determining where and when they are expressed. They have identified insertional mutations in a number of these genes and are characterizing the chemical composition of the walls from the mutants. However, to date they do not have convincing changes in cell wall composition in any of the mutants or in antisense/cosuppression lines for some of the genes. Because of the large number of related genes, it seems possible that many of the genes have functional duplicates that mask the effects of mutations that inactivate one of the genes. It may be possible to overcome this problem by using methods, such as antisense or cosuppression, that permit silencing of the expression of target genes in transgenic plants. Although the analysis of the wall remains an unusually difficult problem, Somerville believes that the new tools of functional genomics will produce some fresh insights during the coming years.[2]

Shauna Somerville
Mechanisms of Disease Resistance

Powdery mildew diseases occur on more than 9,000 plant species, including agriculturally important field and horticultural crops. The powdery mildew pathogens are obligate, biotrophic fungal pathogens that grow only on living host tissues. To successfully colonize a host, biotrophic pathogens must strike a balance between drawing sufficient nutrients from the host to thrive but not so much that the host dies. The powdery mildews extract nutrients and water from their hosts via a haustorium—a fungal structure encapsulated by an invagination of the host plasma membrane. This specialized host membrane is the site of nutrient transfer to the powdery mildew pathogen. In addition, the successful powdery mildew isolates must be able to evade or must be tolerant of normal host defenses.

In one of Shauna Somerville's lab projects, postdoctoral fellow John Vogel screened more than 60,000 mutagenized powdery-mildew-susceptible plants for resistant mutants. From this screen, two classes of mutants were expected. In one class, the researchers predicted that the defense responses would be successfully activated when normally they are not. This class includes both mutants in which defense responses are induced following powdery mildew infection, and those in which defense responses are constitutively activated—or turned on all the time. The second class consists of mutants with defects in host compatibility factors—components required by the pathogen for the successful colonization of the host. To aid in classifying the mutants into one of these two classes, Vogel assayed the mutants for three features: the expression of known defense responses, the stage of powdery mildew arrest, and changes in susceptibility to other pathogens. Detailed analysis of four mutant groups was completed.

The researchers found that the mutants in the largest complementation group are characterized by reduced pollen transmission, enhanced accumulation of pathogenesis-related protein 1 (PR1) mRNA, and susceptibility to a closely related powdery mildew, *Erysiphe orontii*. Thus, this group may fall into the class with enhanced defense responses. However, the defenses are not broad spectrum since they are effective only against *E. cichoracearum*.

Mutants in a second group did not exhibit morphological aberration, had enhanced accumulation of PR1 mRNA, and were resistant to two additional biotrophic pathogens, *E. orontii* and *Peronospora parasitica*—the downy mildew pathogen. Surprisingly, these mutants did not produce callose either at sites of fungal penetration, a common host response, or at wound sites. (Callose accumulation in pollen tubes is normal, suggesting that these mutants are not defective in callose synthesis per se.) This mutant group may also fall into the class of mutants with enhanced defense

responses, with the caveat that whatever defense responses are induced they do not include the callose response. This mutant class is potentially interesting for commercial applications since it confers resistance on multiple pathogens.

A third mutant group developed microlesions of dead cells in mesophyll tissue. (The powdery mildew fungus never penetrates beyond the epidermal layer.) These microlesions appear to arise regardless of the presence of the pathogen, and the lesions do not increase in either number or size following inoculation with the powdery mildew pathogen. Thus, although host-cell death of attacked cells—the hypersensitive necrosis response—is often associated with the expression of resistance, the researchers believe that the spontaneous microlesions observed in this mutant group do not play a direct role in disease resistance. PR1 mRNA accumulation is reduced relative to the susceptible wild-type plants, and the disease resistance phenotype is expressed only under high light conditions where the mutants are dwarfed. Under low light conditions, the mutants resemble the wild-type parent in stature and disease susceptibility. Given this spectrum of properties, it is difficult to place the mutants of this group in either of the two predicted classes.

The final mutant group consisted of plants with no significant increase in any of the known defense responses. This mutant is the best candidate for the class in which host compatibility factors have been disrupted or a totally novel defense pathway has been activated.

Relatively little is known about which host components contribute to disease development in susceptible plants. However, with a better understanding of such factors, it seems possible that disease control strategies based on disrupting the successful colonization by the pathogen may offer a useful alternative to current strategies based on known host resistance genes. For example, a typical barley powdery-mildew-resistance gene has a useful life span in the field of only five years. Disease control strategies based on disrupting host compatibility factors may be more difficult for the powdery mildew pathogen to overcome in the field and thus be more stable.

In future studies, John Vogel will clone and characterize the genes from each mutant group. These genes will provide necessary tools both to evaluate any potentially novel defense pathways or pathway regulators uncovered by the mutant screen and to evaluate the hypothesis that genes recovered from this project encode host compatibility factors. The latter genes are potential sources of stable powdery mildew resistance.

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[45]To February 28, 1999
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THE DIRECTOR'S INTRODUCTION

"Staff Associates have come to play a valued role in broadening the scope and novelty of departmental research."

Staff Associates have once again provided some of this year's highlights. The establishment of these independent faculty positions, with a limited duration of about five years, was an innovation started in this department more than 30 years ago. It has proved to be very successful, providing a long succession of scientists with an environment in which they can work undisturbed, typically with one associate, on innovative projects that would be hard to pursue under other circumstances. In recent years, the quality and success of the department's Staff Associates has inspired other institutions, including the Whitehead Institute, the Fred Hutchinson Cancer Research Center, the University of Texas Southwestern, and the National Cancer Institute, to initiate similar programs. Within the department, Staff Associates have come to play a valued role in broadening the scope and novelty of departmental research.

This year saw the appointment of two new Staff Associates, bringing the total number back up to our target level of four. Erika Matunis studies stem cells—the rare but critically important cells that retain the ability to renew adult tissues by division and differentiation. *Drosophila* has recently emerged as an important system for studying how stem cells are controlled. These elusive cells in the fly can be directly identified and analyzed using sophisticated genetic and developmental techniques. Matunis focuses on the stem cells that maintain sperm production in males. Her work is revealing genes that control male stem cells, and is uncovering fascinating differences between the cells that support male and female gamete production.

Terence Murphy analyzes chromosome segregation—a subject connected to many other research programs in the department. Most genetic functions are carried out by specific sequences of nucleotides located at particular fixed positions on the chromosomes. Murphy has been studying centromeres—the unique site on each chromosome that directs its attachment to the mitotic spindle and ensures that exactly one of its two replicated copies enters each daughter cell. While working with former Carnegie Fellow Gary Karpen and his group at the Salk Institute in San Diego, Murphy was the first to define a centromere region in a chromosome from a multicellular animal at the molecular level. Surprisingly, however, Murphy, Karpen, and colleagues found that the location and sequences used as a centromere could change under certain circumstances. At Carnegie, he plans to address the molecular mechanisms that control such "epigenetic" changes.

Left: Radiography of adult zebrafish reveals details of skeletal structure. See page 52.

The Staff Associates have also been in the forefront of a major trend that developed this year. For the first time in recent memory, all of our eight Staff Member and four Staff Associate positions are filled. The number of active scientists in the department is at an all-time high, and the complexity and diversity of their projects are beginning to place unprecedented demands on the department's space. In response, we have begun several new renovation projects, and expect to hear the sounds of construction somewhere in the building almost continually during the coming year. One such project will make it possible for Jimo Borjigin to expand her studies of the pineal gland and its role in mediating circadian behavior. A special room is being constructed in which the circadian rhythms of rodents can be automatically monitored and recorded. Staff Associate Alejandro Sánchez Alvarado is also expanding the scope of his research in the molecular biology of planarian regeneration.

The Staff Members are also feeling the space shortage. Marnie Halpern is participating in the zebrafish genome project by constructing a genome-wide collection of deletion chromosomes; i.e., chromosomes that lack small, defined regions of the genome. To construct these valuable genetic tools, it is necessary to grow and examine large numbers of fish. The facility originally constructed to support Halpern's research on developmental signaling has now reached full capacity. Consequently, plans are under way to add a new fish room and to completely renovate the original facility so that it can support a higher density of fish. Together these projects will expand the department's fish-rearing capacity more than twofold. Chen-Ming Fan occupies the only laboratory that has not been upgraded since the building was constructed in 1960. Renovation plans have been drawn up recently that will improve existing space utilization by installing laboratory benches with desks for each member of his growing group.

News of the Department

Our seminar program was highlighted by the twenty-second annual minisymposium entitled "Biological Clocks." Michael Menaker of the



Members of the Department of Embryology, October 1999. First row (from left): Jie Deng, Jimo Borjigin, Valarie Bertoglio, Chris Wiese, Sofia Lizarraga, Marnie Halpern, Jenny Hsieh, Catherine Lee, Kelly Liu. Second row: Ben Remo, Jamie Fleenor, Bruce Hodess, Ella Jackson, Ellen Cammon, Dianne Stewart, Rachel Cox, Tim Mical. Third row: Xing Sun, Biswajit Das, Joe Gall, Lijun Zhang, Dongli Huang, Jenny Liang, Laura Buttitta, Rosa Alcazar, Eileen Hogan, Shannon Fisher, Amy Rubinstein, Pat Cammon. Fourth row: Nick Marsh-Armstrong, Don Brown, Lisa Timmons, Ryan Sterner, Luiz Pentaleno-Filho, Alton Etheridge, Nicole Greider, Michel Bellini, Phil Newmark, Bill Kelly, Rejeanne Juste, Paul Megee, Bri Lavoie, Haochu Huang, Melissa Pepling, Zengfeng Wang, Ting Xie, Nicole Mozden, Horacio Frydman, Andy Fire, Terence Murphy, Zheng'an Wu, Allan Spradling, Yixian Zheng

University of Virginia, Michael Roshbash of Brandeis University, Detlef Weigel of the Salk Institute, Martin Raff of University College, London, Carol Greider of the Johns Hopkins University School of Medicine, and Cynthia Kenyon of the University of California, San Francisco, each presented a one-hour talk.

Support for research in the department comes from a wide variety of sources. Doug Koshland and I, plus various members of our laboratories, are employees of the Howard Hughes Medical Institute. Others are grateful recipients of individual grants from the National Institutes of Health, the John Merck Fund, the G. Harold and Leila Y. Mathers Charitable Foundation, the American Cancer Society, the Jane Coffin Childs Memorial Fund, the Damon Runyon-Walter Winchell Cancer Fund, the Pew Scholars Program, the Alfred P. Sloan Foundation, the National Science Foundation, and the Arnold and Mabel Beckman Foundation. We also remain indebted to the Lucille P. Markey Charitable Trust for its support.

—Allan Spradling

Jimo Borjigin
Circadian Rhythms

Scientists in the Borjigin lab are interested in understanding the cellular and molecular mechanisms that govern circadian rhythms. The pineal gland expresses melatonin, one of the most dramatically regulated hormones, which, because it links the body's physiological processes to the daily cycle of sunlight and darkness, provides an ideal model system for circadian-rhythm research. The scientists are focusing on two aspects of pineal rhythms: first, they are trying to identify the intracellular and extracellular molecules that control or influence pineal rhythms, and second, they are examining the mechanisms by which neuronal and humoral inputs lead to nightly production of melatonin.

Utilizing a sensitive subtractive hybridization technique, the researchers have isolated night pineal cDNAs encoding the serotonin N-acetyltransferase (NAT), a novel PIneal Night-specific ATPase (PINA), and Patched 1 (Ptc1). NAT is the rate-limiting enzyme of melatonin formation; PINA is a novel, alternatively spliced, pineal, and night-specific form of the Wilson disease (WD) gene; and Ptc1 is a tumor suppressor and a receptor for Hedgehog proteins that play a key role in embryonic development. The group's work indicates that the nightly production of all three messages are controlled primarily by cAMP signaling and that the protein products are sensitive to light stimulation during dark periods. In addition to NAT, PINA, and Ptc1, the scientists have identified a number of other diurnally regulated mRNAs in the rat pineal that appear to be important in pineal circadian functions. Understanding the role of these diurnal intracellular molecules in pineal circadian function is one of their main goals.

To facilitate molecular dissection of circadian-rhythm pathways, the group has established methods to examine in vivo the influences of extracellular molecules on pineal circadian rhythms. They have also developed techniques to express foreign proteins in pineals of live animals at high efficiency, which will allow the Borjigin lab to explore the mechanism of action of newly discovered genes.

Donald D. Brown
Amphibian Metamorphosis

The fertilized egg of the frog *Xenopus laevis* takes about one week to become a feeding tadpole. Three days later the tadpole forms a small thyroid gland. As the tadpole grows, the gland enlarges and synthesizes increasing amounts of thyroid hormone (TH). The concentration of this hormone controls the metamorphosis of tadpoles into frogs. TH is known to function by binding to a protein located in the nucleus of target cells, which in turn activates or represses genes. The Brown group has studied metamorphosis as a set of complex genetic programs, which are controlled by this single, simple molecule.

How can a simple hormone trigger such very diverse responses in most of the tissues of a tadpole? To find out the answer, the scientists began by identifying many of the genes that are up- or down-regulated by TH in several target tadpole

organs. These include the tail, which dies and is resorbed, the limb, which grows and differentiates, and the intestine, which is completely remodeled during metamorphosis. Next the researchers found the exact cell types that express these genes. By sequencing the genes that are regulated by TH, the team identified the protein that each gene encodes. Knowing the identity of the gene and where and when it is expressed provided clues on the possible role of each gene in metamorphosis. One conclusion has been that the extensive thyroid-hormone-induced cell death that occurs consists of multiple genetic programs.

Recently, the Brown group has been aided by the development of a technique called transgenesis, in which any isolated gene can be introduced into the genome of a *Xenopus* embryo before first cleavage.[1] This guarantees that all the cells of the embryo and the tadpole will contain the gene. Using this powerful method, the Brown group has tested many of their genes and developed functional assays for gene function in metamorphosis.

Some of the discoveries that the group has made are as follows:

The hormone prolactin, previously thought to be a juvenile hormone for anuran tadpoles, does not retard metamorphosis. However, it specifically inhibits the tail resorption program, yielding a powerful tool in the search for the basis of cell death in the tail (Fig. 1).

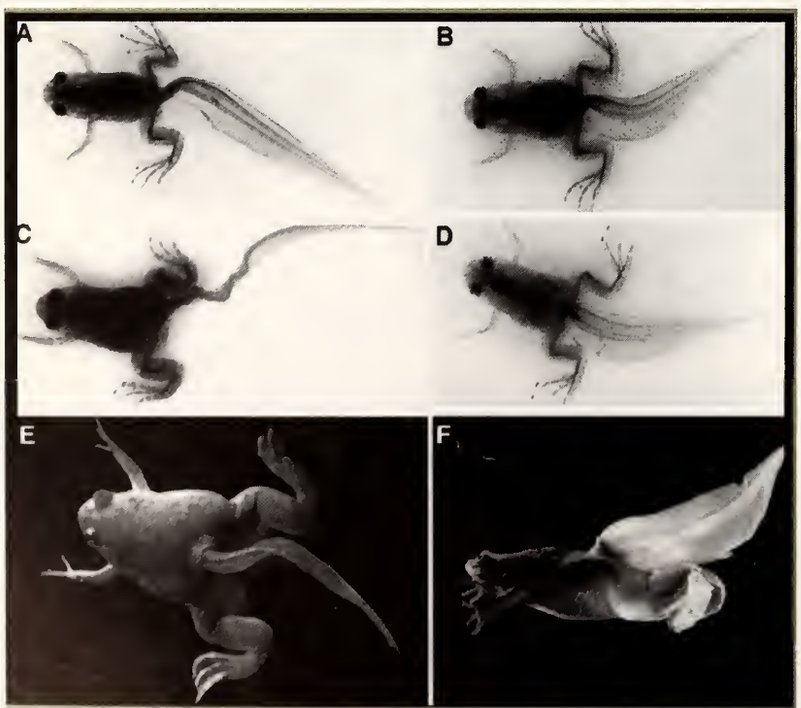


Fig. 1. This is a picture of frogs with overexpressed prolactin. The result is inhibited tail reabsorption.

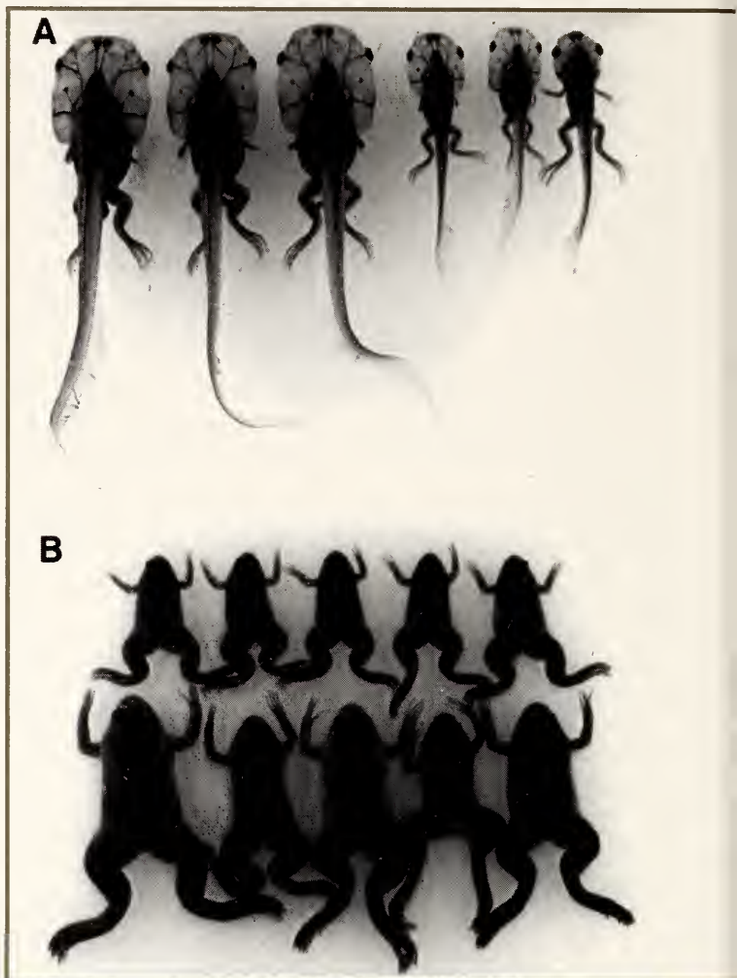


Fig. 2. Both control tadpoles and frogs, and those overexpressing growth hormone, are shown.

Growth hormone has the same effect on tadpoles and frogs as it does on mammals. It dramatically increases growth (Fig. 2).

The group has identified two independent methods to inhibit functions that are dependent on TH; namely, overexpressing either a gene encoding an enzyme that destroys the hormone, or an altered form of the hormone's receptor called a dominant negative inhibitor. Both kinds of genes are introduced under the control of a specific promoter. The resulting transgenic animals are unable to complete specific sets of functions. These new methods are making possible a new approach to the age-old problem of amphibian metamorphosis.

1 Kroll, K. L., and E. Amaya, *Development 122*, 3173-3183, 1996.

CHEN-MING FAN

Generating Mouse Models for Human Genetic Diseases

Mouse models provide a powerful tool to study human diseases and to allow molecular testing of the underlying mechanisms involved. The primary goal of Fan's research is to generate mouse models for better understanding of human development and genetic diseases. The scientists hope that the information obtained through basic research will be used to find cures or minimize the impact of the genetic aberration.

The group has generated the mouse models lacking *Sim1* and *Sim2* function. *Sim1* and *Sim2* are two mouse homologs of the *Drosophila sim* gene, which controls the development of the central nervous system midline cells in the fly. The group has cloned and characterized these mouse *Sim* genes,[2] and both *Sim1* and *Sim2* gene functions have been inactivated in the mouse via homologous recombination.

The analyses of *Sim1* mutant mice have led to the conclusion that *Sim1* controls the development of the anterior periventricular nucleus, the paraventricular nucleus, and the supraoptic nucleus of the hypothalamus. Consequently, in the *Sim1* mutant, the neuroendocrine peptide hormones such as corticotropin-releasing hormone, thyrotropin-releasing hormone, somatostatin, vasopressin, and oxytocin are not produced by the hypothalamus. The severe depletion of these homeostasis hormonal peptides most likely causes the perinatal lethality of *Sim1* mutant mice.[3] The scientists have also found that there was a mutant mouse generated in the 1960s that displayed identical hypothalamic phenotype as *Sim1*. They showed that *Sim1* and this mutated gene *Arnt2* are coexpressed in the hypothalamus and that their protein products can bind to each other, suggesting that they function together to control the development of the hypothalamus.[4]

To their surprise, *Sim1* heterozygous mice are obese (Fig. 3). Recently, many of the genetic components involved in mouse obesity have been identified. While the lateral and ventral hypothalamic nuclei have been implicated to control satiety, the role of the paraventricular region in obesity is less clear. The researchers are currently investigating how *Sim1* fits into the genetic pathway of obesity. An obese patient has been identified by Dr. Andrew Zinn of Southwestern University to carry a mutation in the *SIM1* gene. Collaborative efforts have been initiated to use the Fan mouse model to understand this corresponding human condition and possibly develop a corrective procedure.



Fig. 3. An obese *Sim1* heterozygous mouse is shown on the left. To the right is a control.

Preliminary analysis of the *Sim2* mutant suggests that *Sim2* is required for the proper development of specific craniofacial structures. The primary defects when this gene is absent are cleft palate, nasal bone abnormality, and trigeminal nerve reduction. This is consistent with the possibility that *Sim2* may contribute to aspects of Down's syndrome pathology (the human *SIM2* gene is located within the Down's syndrome "critical region" of chromosome 21). Detailed documentation of the affected cartilage and bones is the immediate goal. However, overexpression of *Sim2* does not appear to recapitulate the trisomy phenotype of Down's syndrome (DS), most likely due to the requirement of multiple genes on chromosome 21 to reproduce the DS phenotype.

2 Fan et al., *MCN 7*, 1-16, 1996.
3 Michaud et al., *Genes & Development 12*, 3264-3275, 1998.
4 Michaud et al., *Mechanisms of Development*, in press.

ANDREW Z. FIRE

The Fire lab is interested in the mechanisms by which cells choose their fates during development, and in particular the means by which asymmetry is generated. Two types of developmental decisions are being studied: early developmental decisions between germ line and somatic fates, and later decisions between different somatic fates (e.g., skin and muscle).

As an experimental organism, the group uses *C. elegans* because of its genetics, the ease of experimental manipulation, and the simplicity of its development. The studies of germ line/soma decisions have focused so far on questions of how these two cell populations differ in their capacities for gene expression. It appears that germ cells have a number of highly active mechanisms to limit the expression of somatically expressed genes. Some of these mechanisms may act at the level of gene context or chromatin structure. The scientists would like to understand how this regulation is mediated and what features of gene expression allow specific cells to maintain germ line capacity to produce subsequent generations of the organism.

Much of the analysis of somatic fates has focused on the formation of different muscle types during embryonic development. Studies of muscle development have been facilitated by the wealth of available information about their morphology, function, and terminal differentiation products. Myogenic decisions during embryogenesis and larval development result in a variety of different muscle types in *C. elegans*. The analysis at the Fire lab is directed toward an understanding of general processes responsible for the choice of cell type and subsequent tissue patterning. This includes what types of factors control and carry out decisions to undergo myogenesis; what the molecular nature is of the blastomere identities that are set up in the early embryo and "remembered" during cell proliferation; how lineage information is interpreted to determine cell fate; and if there are similar activities regulating myogenesis for nematode and analogous vertebrate muscles.

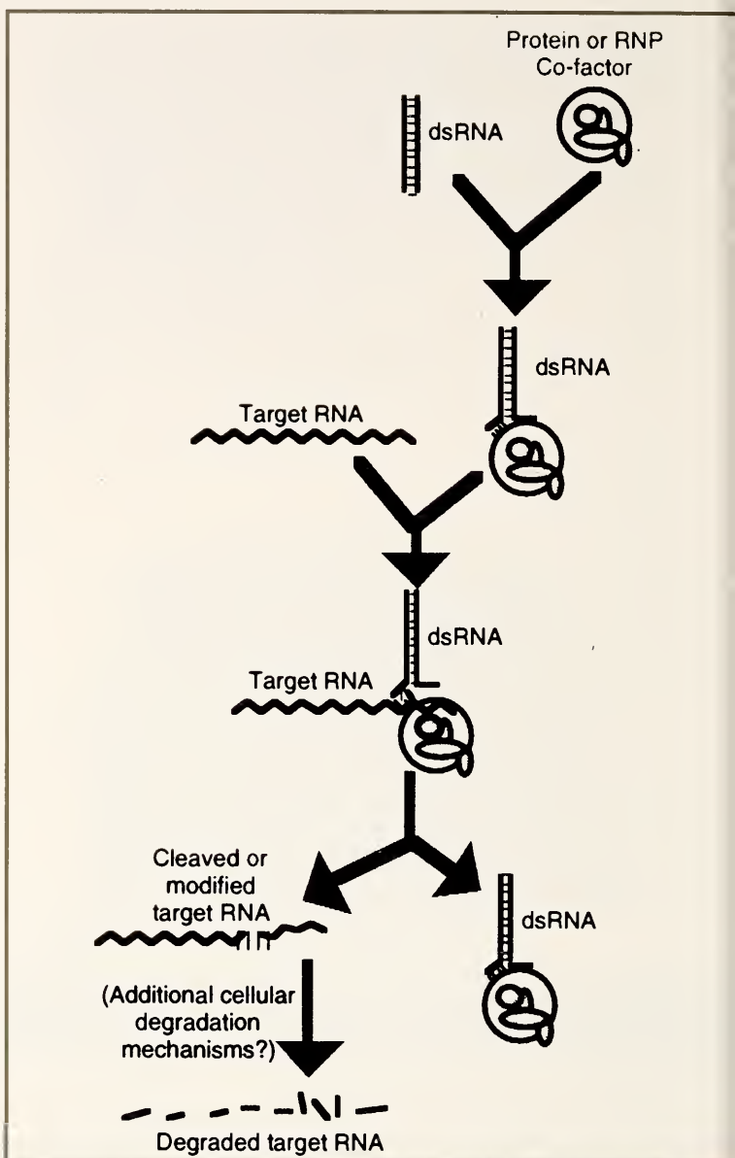


Fig. 4. RNAi model.

Much of current biological research is technique driven. A portion of Fire's research effort is aimed at producing tools to address each of the following questions for a molecule of interest: When and where is the molecule present? What happens if expression is prevented? What happens if the molecule is provided at an inappropriate time or place? What other molecules interact? The lab has been involved in developing methods to answer these questions based on DNA-mediated transformation, as well as on wholemount, in situ hybridization and genetic-deficiency screening. In the course of this work, the scientists have developed a number of vectors for DNA transformation and analysis of expression patterns that have been useful both for their own work and for work in other

labs in the field. A major technical challenge for *C. elegans* researchers over the next few years will be to develop methods for precisely targeting mutations to specific genes in their normal chromosomal context.

Joseph G. Gall

The Cajal Body: Assembly Site for the Nuclear Transcription Machinery

The first step in the expression of any gene is the formation of an RNA copy of its DNA. This step, referred to as transcription, takes place in the cell nucleus. Transcription requires the enzyme RNA polymerase and a multitude of processing factors, which modify the primary transcript before it is exported to the cytoplasm as the functional messenger RNA. Although the biochemical details of transcription and processing of RNA are known in considerable detail, relatively little is known about their cellular organization. It has been generally assumed that the polymerase and various additional factors are recruited separately to active genes on the chromosomes. Researchers in the Gall lab have recently proposed an alternative model in which the RNA machinery is preassembled as a unitary particle completely separate from the chromosomes. This particle, which they call a *transcriptosome*, is recruited to the sites of active genes, bringing the entire transcription machinery to the genes as a single packet. This model is based on cytological and molecular studies of animal cell nuclei.

Much of the lab's work is carried out on oocytes of the frog *Xenopus*. An oocyte is an egg before it is laid by the female; in *Xenopus* it is a single giant cell up to 1.5 mm in diameter. The nucleus of the oocyte is equally large, about 0.4 mm in diameter, and can be hand-isolated from the oocyte. For historical reasons, the oocyte nucleus is usually called the germinal vesicle, or simply GV. The large size of the GV permits one to examine the contents of a cell nucleus in unprecedented morphological detail. At the same time, many biochemical studies can be carried out on single hand-isolated GVs or small numbers of GVs.

The scientists have focused their attention on structures in the GV called Cajal bodies, first seen in the nuclei of nerve cells nearly 100 years ago by the Spanish neurobiologist Ramón y Cajal. They have shown that Cajal bodies contain many, if not all, factors required for transcription and processing of messenger RNA, including RNA polymerase II and factors required for initiation, splicing, cleavage, and polyadenylation of the RNA transcript. Remarkably, Cajal bodies also contain the special factors required for transcription and processing of ribosomal RNA (polymerase I and its associated factors), as well as polymerase III, which transcribes certain small RNAs. The GV is an ideal system in which to study not only the sites where specific factors are found, but also where they are assembled into macromolecular complexes. This can be done by injecting factors into the cell and observing where they go initially, and where they end up after a longer time. From experiments of this sort, the scientists conclude not only that the transcription machinery exists in the Cajal bodies, but that a significant fraction of it must be assembled there.

In future experiments, the Gall lab hopes to learn how various factors are recruited to the Cajal bodies and how they assemble into the large transcriptosome complexes. The researchers are also trying to isolate transcriptosomes from oocytes to determine their composition and structure in more detail.

Marnie Halpern

The Halpern laboratory uses genetic approaches in the zebrafish to study how signaling pathways in a vertebrate embryo lead to correct patterning of adult structures. Several mutations have been identified that transform the fates of embryonic cells so that cells that should form muscle (a more dorsal fate) give rise instead to blood (a ventral fate). Surprisingly, for one of the identified genes, *chordin*, which encodes an antagonist of ventralizing signals, some mutant embryos can sufficiently regulate to develop into fertile adults. However, these fish have defective skeletons and abnormal or missing caudal fins (Fig. 5). A normal vertebral column is restored in the adult by overexpressing



Fig. 5. Radiography of adult zebrafish reveals details of skeletal structure. On top is a homozygous *chordin* mutant with irregularly shaped bones in the caudal skeleton and no tail fins. On the bottom is a *chordin* mutant whose skeletal defects were corrected by the introduction of *chordin* RNA during embryonic development several weeks before the formation of the vertebral column. The images were taken in a Faxitron MX-20 cabinet x-ray, with a four-second exposure at threefold magnification.

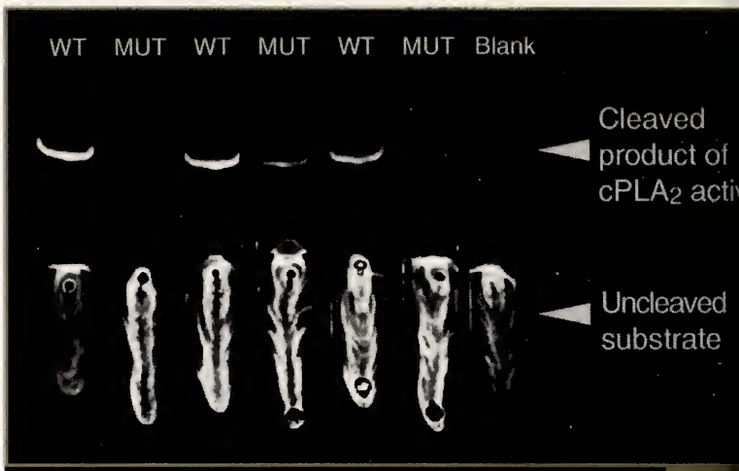


Fig. 6. Visualization of the cleavage product of cytosolic phospholipase A_2 ($cPLA_2$) using fluorescent lipid substrates and thin layer chromatography is an efficient way to monitor the activity present in single embryo extracts. This method is used to identify mutations (MUT) in the zebrafish that alter normal levels of enzymatic activity (WT).

chordin RNA in the mutant embryo. This finding reveals an early requirement for Chordin for correct patterning of the adult skeleton, and has led to a search for other genes involved in bone differentiation and morphogenesis. Through a mutational screen of live, anesthetized fish using x-rays, postdoctoral fellow Shannon Fisher aims to identify dominant mutations that perturb the skeleton, and thereby identify other new genes that are involved in specifying and patterning adult bones.

Studies of zebrafish mutants are also revealing molecular mechanisms that underlie development of the vertebrate central nervous system, and most recently, left-right differences in the vertebrate brain. In collaboration with Chris Wright's group at the Vanderbilt Medical School, the Halpern group found that zebrafish *cyclops* encodes a *nodal*-related, TGF-beta signaling family member that is involved in patterning the midline of the neural tube. Postdoctoral fellow Amy Rubinstein has been examining other genes transcribed in the early embryo that depend on Cyclops signals for their correct expression. Interestingly, *cyclops* is also expressed asymmetrically later in embryogenesis in two places: the left lateral-plate mesoderm, which is thought to influence patterning of the heart, and the left dorsal forebrain. Postdoctoral fellow Jennifer Liang is exploring how transient left-sided signaling in the brain is regulated and what its functional significance may be. To do this, mutant embryos with midline defects are transiently rescued by RNA injection, but not long enough to restore left-sided gene expression in the brain. Thus, the role of asymmetric signals in the developing forebrain can be assessed by the consequences on the neuroanatomy and behavior of the adult fish.

To capitalize on the accessibility and optical clarity of the fish embryo, methods have also been devised for direct visualization of protein action during signaling processes. Initially, postdoctoral fellow Steve Farber focused on phospholipase A_2 (PLA_2), which cleaves phospholipids to liberate potent lipid signals and is present in high levels in the developing zebrafish. The subcellular localization of PLA_2 activity was revealed in living embryos using fluorescently quenched lipid substrates that fluoresce upon cleavage. Moreover, uptake of these lipid substrates by cells of the intestinal epithelium permits monitoring of lipid metabolism in the newly formed digestive system. One aim is to use these and other fluorescent reporters in genetic screens for functional modulators of activity (Fig. 6) and for real-time imaging of enzyme action during development.

Douglas Koshland

Replicated chromosomes (sister chromatids) acquire three specific structural features that are important for chromosome segregation in mitosis. First, each sister chromatid has a centromere that mediates the attachment and the movement of chromosomes on the spindle. Second, sister chromatids are paired. Pairing is needed to establish a stable bipolar attachment of sister chromatids to microtubules of the mitotic spindle, which in turn ensures that sister chromatids segregate from each other during anaphase. Additionally, the dissolution of pairing appears to be a key event in governing the onset of chromosome segregation. Third, sister chromatids are condensed. This condensation helps to minimize entanglement of chromosomes while they move during mitosis, and shortens the chromosomes so that they are always displaced from the cytokinetic furrow at the end of mitosis.

Much of our understanding of mitotic chromosome function and structure has come from the study of vertebrate and invertebrate cells using cytology and established biochemical assays. More recently, studies using the budding yeast, *Saccharomyces cerevisiae*, have also begun to make significant contributions to the field. This simple eukaryote is amenable to extensive genetic analysis; and researchers have determined the specific DNA sequences required for the function of centromeres, telomeres, and origin of replications. With this knowledge it has been possible to manipulate the structure of endogenous chromosomes, as well as generate novel artificial chromosomes. Genetic and biochemical studies have also identified key genes encoding histones, topoisomerases, centromere proteins, and cell cycle regulators. Mutations in these genes provide important tools to manipulate both chromosomes and the cell cycle in vivo.

The Koshland group has developed three new assays for analyzing mitotic chromosomes in the budding yeast: an in vitro assay for centromere-microtubule interactions, a fluorescent in situ hybridization assay for following sister chromatid pairing and condensation, and a chromatin immunoprecipitation assay for monitoring in vivo binding of proteins to chromosomes at specific sites. Using these assays and yeast genetics, the group has characterized yeast centromere function in vitro, identified and characterized centromere components (Mif2p, Cse4p, and Cep3p), identified a potential nucleosome-based centromere core conserved from yeast to humans, and revealed both centromere movement and regulation during the cell cycle. Koshland's team has also identified and characterized two new classes of proteins important for sister chromatid pairing and condensation. The first is Pds1p: a cell cycle regulator important for the control of the metaphase/anaphase transition, for the exit of mitosis, and for cell cycle arrest in response to DNA and spindle damage. The second class, Smc proteins, is a family of chromosomal proteins, conserved from bacteria to humans that are essential in diverse eukaryotes for processes involving higher-order chromosome structure, including chromosome condensation, sister chromatid cohesion, dosage compensation, and recombination repair. Recently the scientists identified non-Smc subunits required for condensation and cohesion. The study of these proteins provided novel links between cohesion and condensation, and between cohesion and DNA replication. The team has also been able to map cohesion sites on chromosomes, demonstrating that the centromere nucleates the assembly of cohesion factors onto at least several kilobases of DNA flanking the centromere. Further analyses of these proteins and sites will provide insight into higher-order chromosome folding, as well as genome organization and stability.

Erika Matunis

Stem cells have the ability to replicate indefinitely and can also give rise to more specialized tissue cells in response to appropriate environmental cues. Because of their unique regenerative properties, stem cells are the focus of much research. However, because stem cells are usually rare and reside in complex environments, little is known about how they behave in vivo. Since the regulatory mechanisms discovered in simpler model organisms often apply to complex systems as well, the Matunis lab is studying stem cells that sustain

spermatogenesis in the fruit fly *Drosophila melanogaster*. Stem cells in the *Drosophila* testis are easy to identify, reside in a well-defined environment, and are amenable to both experimental and genetic manipulation. The researchers' goal is to use genetics to identify the environmental cues that regulate stem cells in the *Drosophila* testis.

Spermatogenesis begins when a germ line stem cell (gsc) divides, producing one cell that remains a gsc and can replicate indefinitely, and another cell (called a gonial cell) with a very different fate. Unlike gscs, gonial cells cannot divide indefinitely. Instead they differentiate, ultimately producing a bundle of sperm. When the gsc divides then, how does it give rise to two cells with such different fates? Perhaps the gsc receives a signal from its environment that allows it to remain a stem cell, while the gonial cell is displaced away from the signal, thus causing it to lose the stem cell fate. This type of mechanism is hypothesized to operate in many stem cell systems, but has been extremely difficult to prove. Interestingly, gscs in the *Drosophila* testis (Fig. 7; indicated by the arrowhead) are attached to a small cluster of cells called the hub (indicated by the thin arrow), and as gonial cells are created (thick arrow), they are displaced away from the hub. The hub is thus a good candidate for a source of signals that influence the gsc divisions. But does such a signal exist? To search for it, researchers can remove genes that encode signaling molecules from cells in the testis and look for a corresponding loss of gscs. Such genes should encode signals that are needed to maintain the gsc fate. Using this approach, Matunis's lab has found that the Jak-Stat signaling pathway is needed to maintain gscs. In this pathway, receptor-associated cytoplasmic protein tyrosine kinases (Janus, or Jak kinases) are catalytically activated upon ligand binding, and activate transcription factors in the signal transducer and activator of transcription (Stat) family. The scientists are currently trying to determine if the Jak-Stat pathway is activated directly in the gscs, or in nearby cells in their environment. They are also looking for the ligand that activates the Jak-Stat pathway during spermatogenesis. Once this ligand is identified, they will determine which cells in the testis are producing it. This should give them a detailed picture of how an environmental cue regulates stem cells at a level of detail not possible in more complex stem cell systems. Furthermore, since Jak-Stat signaling is required for the function of mammalian stem cells, notably during hematopoiesis, the knowledge gained here will likely apply to such stem cell systems.

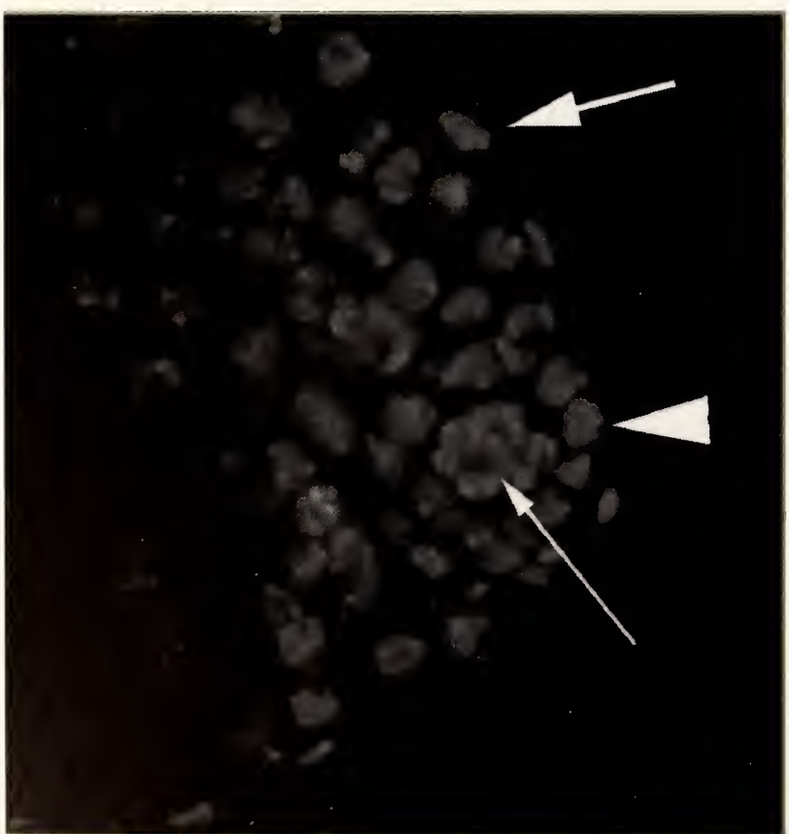


Fig. 7. The arrowhead in this image indicates a germ line stem cell (gscs) in the *Drosophila* testis. They are attached to a small cluster of cells called the hub (thin arrow). As gonial cells are created (thick arrow), they are displaced away from the hub.

Terence Murphy

The term *chromosome* means colored body, but this description hardly does them justice. As the main bearers of genetic information in the cell, chromosomes serve an essential role throughout the cell cycle. Yet their primary role is not revealed until cell division, at which time they undergo an intricate series of movements to ensure that each daughter nucleus receives an identical complement of genetic material. The fidelity of this process is amazing: natural chromosomes in the budding yeast *Saccharomyces cerevisiae* are lost only once in

every 100,000 divisions. The consequences of mistakes are equally staggering. Gain or loss of a chromosome (aneuploidy) in every cell of an organism is typically lethal or results in severe birth defects such as Down's syndrome. Aneuploidy is also associated with cancer progression, aging, Alzheimer's disease, developmental disorders such as Robert's syndrome, and even one type of bacterial infection, thus providing a considerable impetus for studying the mechanics of chromosome inheritance.

Chromosome inheritance requires a coordinated series of interactions between chromosomes and the mitotic spindle. Spindle attachments primarily occur at a single site on each chromosome called the centromere, which nucleates a large proteinaceous structure called the kinetochore. The kinetochore attaches to microtubules and helps direct chromosome movements along the spindle. But how do centromeres work? For many years, researchers have postulated that centromeres would function in a manner analogous to gene promoters—that is, unique DNA sequences on the chromosome would be bound by specific DNA-binding proteins, which in turn would mediate the attachment to microtubules. However, a growing body of data suggests that in many eukaryotes this is not the case. Centromeres in multicellular eukaryotes are primarily composed of highly repetitive satellite sequences that vary substantially from one centromere to the next, and are not evolutionarily conserved. Also, centromeres have been found to change their functional state (i.e., turn off or turn on) without detectable changes in DNA sequence. These paradoxes have led researchers to propose that centromeres are partially epigenetic: that is, centromeres are specified not by DNA sequence but by a special mark on the chromosome, such as a DNA modification or a unique chromatin structure that can be copied from the original centromere to the nascent centromeres during chromosome replication.

An epigenetic model for centromere function is consistent with the available data, but very little is known about the nature of the mark or how it is copied during chromosome replication. Murphy is constructing an assay in *Drosophila* that will directly measure the frequency at which centromeres are epigenetically turned off by assaying the behavior of chromosomes with two centromeres (dicentric chromosomes)(Fig. 8). This assay will in turn allow the identification of genes that are involved in copying the centromere mark during chromosome replication, as well as other genes connected with centromere function such as microtubule-based motors. To complement this assay, Murphy is also constructing a set of in vivo tools that will aid in the analyses of genetic mutations that affect chromosome inheritance. Together, these tools will allow dissection of the genes and mechanisms controlling the behavior of chromosomes during cell division.



Fig. 8. The typical behavior of a dicentric chromosome during anaphase is shown. The two centromeres are moving to opposite poles, stretching the intervening chromatin into a dicentric bridge (arrow) that will eventually break. Chromosomes are shown in dark gray, centromeres in light gray. (Image courtesy of Byron Williams.)

ALEJANDRO SÁNCHEZ ALVARADO

Animal Regeneration

Regeneration is a fundamental attribute of all living things, whether it be simple tissue restoration

or the complete replacement of lost body parts such as limbs, tails, or even heads. As a biological problem, regeneration began to be studied formally over 250 years ago in crustaceans by René-Antoine Ferchault de Réaumur (1683-1757), and soon after in hydra by Abraham Trembley (1710-1784). A long-standing problem of biology, regeneration in metazoans still awaits a satisfactory mechanistic explanation. The laboratory's goal is to identify and study the molecular components underpinning this phenomenon. The researchers are approaching the problem by analyzing and manipulating the regenerative properties found in both vertebrate and invertebrate organisms.

As a vertebrate model, the Sánchez Alvarado lab uses amphibian tadpoles (*Xenopus laevis* and *Rana temporaria*), whose tails regenerate to completion after amputation. These studies aim to identify a complement of genes operating during tail regeneration. To date, nearly 20 genes upregulated by the process of regeneration have been identified in *Rana temporaria* tadpoles, and their temporal and spatial expression patterns are being elucidated.

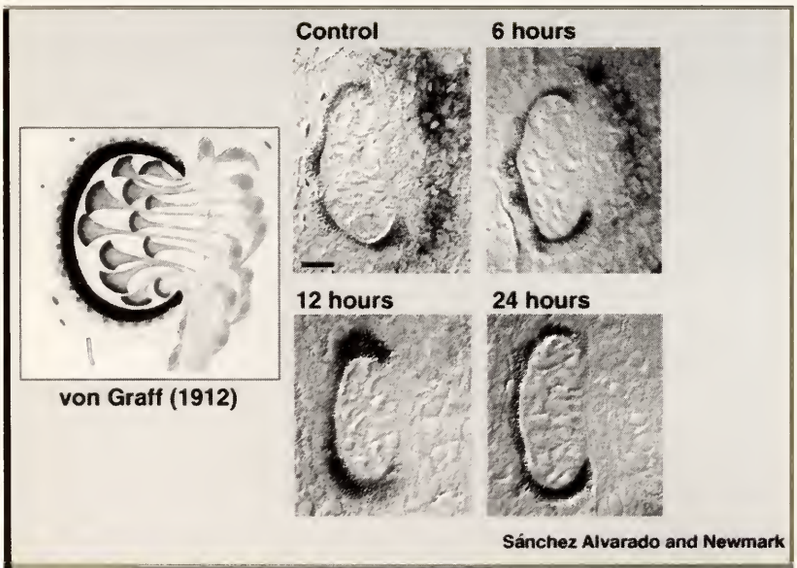


Fig. 9. Abrogation of gene expression in planarians using double-stranded RNA is shown here. A schematic representation of the planarian photoreceptor is shown on the left; the pigment cup is c-shaped and the retinular, light-sensing cells in light gray (after von Graff, L. (1912-1917), in *Klassen und Ordnungen des Tier-Reichs*, vol. 4, H. G. Bronn, ed., C. F. Winter'sche Verlangshandlung, Leipzig). The light-gray cells express the gene for opsin, a protein involved in mediating phototransduction. The control panel shows a section of the planarian *Schmidtea mediterranea* photoreceptor injected with water as a control, and also shows the cells where opsin RNA is present as detected by in situ hybridization (in dark gray). The remaining panels show what happens to the opsin RNA 6, 12, and 24 hours after opsin double-stranded RNA (instead of water) is injected into the animals.

The invertebrate organisms the scientists chose are members of the phylum Platyhelminthes and are commonly known as planarians, or flatworms. The uncanny regenerative abilities of these triploblastic animals have been known for many years. In fact, work on planarian regeneration dates back to the work of the German naturalist Peter Simon Pallas (1741-1811) and has continued ever since. The group studies *Schmidtea mediterranea*, a stable diploid with a genome size slightly larger than that of *Drosophila*. Thus far, the researchers have identified over 30 regeneration-modulated and regionally enriched genes, and have shown that gene expression in these animals can be silenced by double-stranded RNA. More recently the group has succeeded in specifically labeling planarian neoblasts—the stem cell population at the root of the regenerative prowess of planarians. With the tools of ablating gene expression and labeling neoblasts, the scientists will be able to vertically integrate what is learned from planarians into the study of regeneration in higher organisms.

Future research in the laboratory will involve the creation of transgenic planarians using neoblasts as vectors for the introduction of DNA, as well as a more extensive delineation of the transcription programs activated during the events of metazoan regeneration using DNA microarrays. Further information on the laboratory's activities can be found at http://www.ciwemb.edu/links/research_blurbs/sanchez/sanchezresearch.html.

Allan Spradling
Structure and Function of Female Germ Cells

Each generation, germ line cells carry out two major functions. First, they propagate their own intricate, information-rich contents in an essentially undamaged state, thereby continuing an unbroken chain of inheritance from their germ cell ancestors stretching back billions of years. Secondly, female germ cells choreograph early embryonic development, which establishes essen-

tial conditions for germ line-derived somatic cells to produce a new, but transient organism. The Spradling lab studies several of the processes germ cells use to accomplish these fundamental tasks by conducting molecular genetic studies of the fruit fly *Drosophila* and of mice.

How can germ line cells proliferate, seemingly without limit, while somatic cells age and die? One group of cellular organelles, the mitochondria, produce energy by oxidative processes that generate highly reactive and potentially damaging by-products. Despite this, mitochondria contain their own small genome, encoded by mitochondrial DNA. Damage to mitochondrial DNA has recently been shown to cause several human diseases, and to occur spontaneously in aging somatic cells. Spradling's group has begun to analyze how new mitochondria are produced during the process of egg formation and to learn how germ cells are able to furnish succeeding generations of somatic cells with functional, undamaged mitochondrial genomes.

Spradling believes that keys to understanding this and several other aspects of germ cell biology can be found during a little-studied, early stage of germ cell development, when small groups of germ cells transiently become interconnected with one another into cell clusters. During this time, membrane-rich cellular constituents, including mitochondria, aggregate within an unusual structure—the fusome—that extends throughout all the cells in the cluster. The scientists are identifying the genes and mechanisms used to program cell cluster and fusome formation, and are gaining insight into the function of these processes.

Even earlier in their generational cycle, *Drosophila* germ cells proliferate extensively as stem cells. Germ line stem cells represent one of the best systems currently available to study the molecular mechanisms that control stem cell proliferation—a fundamental process underlying the maintenance of many adult tissues. The lab's work has implicated the regulated translation of stored messenger RNAs as a critical process used by stem cells and has identified a likely key target of such regulation. Moreover, the researchers discovered extracellular signals from nearby somatic cells that are needed to maintain the stem cell's fate. They are also studying mechanisms that germ line cells use to silence the expression of unwanted genes, such as those of invading viruses and transposable elements.

Finally, Spradling and his lab members recognize that progress in biology often comes from improved methods. They continue to participate in the *Drosophila* genome project. Their current goal is to further facilitate studies of gene function by isolating insertional mutations in greater than 85% of all genes identifiable in the genome sequence.

Yixian Zheng
Microtubule Nucleation and Organization in Response to Cell Cycle and Developmental Signals

How a cell organizes its interior and how it divides are central questions in cell and developmental biology. Research in the Zheng lab focuses on understanding how different microtubule arrays are nucleated and are organized in response to cell cycle and developmental signals. Microtubules are tiny filaments found in all eukaryotes. They are essential for intracellular organization and mitosis.

The major microtubule nucleation site inside an animal cell is the centrosome. One research avenue in the Zheng lab is to understand the structure and function of the centrosome using *Xenopus* and *Drosophila* as model systems. The centrosome consists of a pair of centrioles and an electron-dense pericentriolar material (PCM), which harbors the activity for microtubule nucleation and organization. The scientists in Zheng's lab discovered a γ-tubulin-containing ring complex (γTuRC) in the two organisms and found that it can nucleate microtubules in vitro. Additionally they found that γTuRC is essential for centrosomes to nucleate microtubules. Zheng's current hypothesis is that the γTuRC is the major microtubule nucleator at the PCM. γTuRC consists of approximately five, presently uncharacterized, proteins in addition to

γ-tubulin. The team is using a combination of molecular genetic, biochemical, and genetic approaches to understand this ring complex. The researchers are particularly interested in addressing how the γTuRC is involved in regulating microtubule-nucleating activity of the centrosome, how it is recruited and assembled at the PCM, and whether (and how) it is involved in centrosome duplication.

Another research direction in the lab is to understand the signals that regulate spindle assembly during mitosis. In animal cells, the transition from interphase to mitosis is accompanied by dramatic changes in cellular architecture such as nuclear envelope breakdown, chromosome condensation, and spindle formation. The reorganization of the interphase microtubule array into a highly dynamic mitotic spindle requires more than the presence of centrosomes and the conversion of cytosol into a mitotic state. Several studies have found that nuclear signals released into the cytoplasm upon nuclear envelope breakdown exert many different effects on microtubule arrays. Recently, the Zheng group discovered that the small nuclear GTPase, Ran, can stimulate microtubule aster and spindle formation in the absence of both centrosomes and chromosomes. These findings suggest that Ran is the nuclear signal that regulates microtubule assembly in mitosis.

Future projects in the lab will involve dissecting the mechanism of the Ran signaling pathway in mitosis. The Zheng lab has shown that RanGTP can stimulate not only microtubule polymerization but also microtubule organization in mitosis. They are now developing assays to help identify the downstream targets of RanGTP.

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[5] From June 7, 1999
[6] To October 31, 1998
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[8] From August 6, 1998
[9] To August 31, 1999
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[12] From January 20, 1999
[13] From June 1, 1999
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THE DIRECTOR'S INTRODUCTION

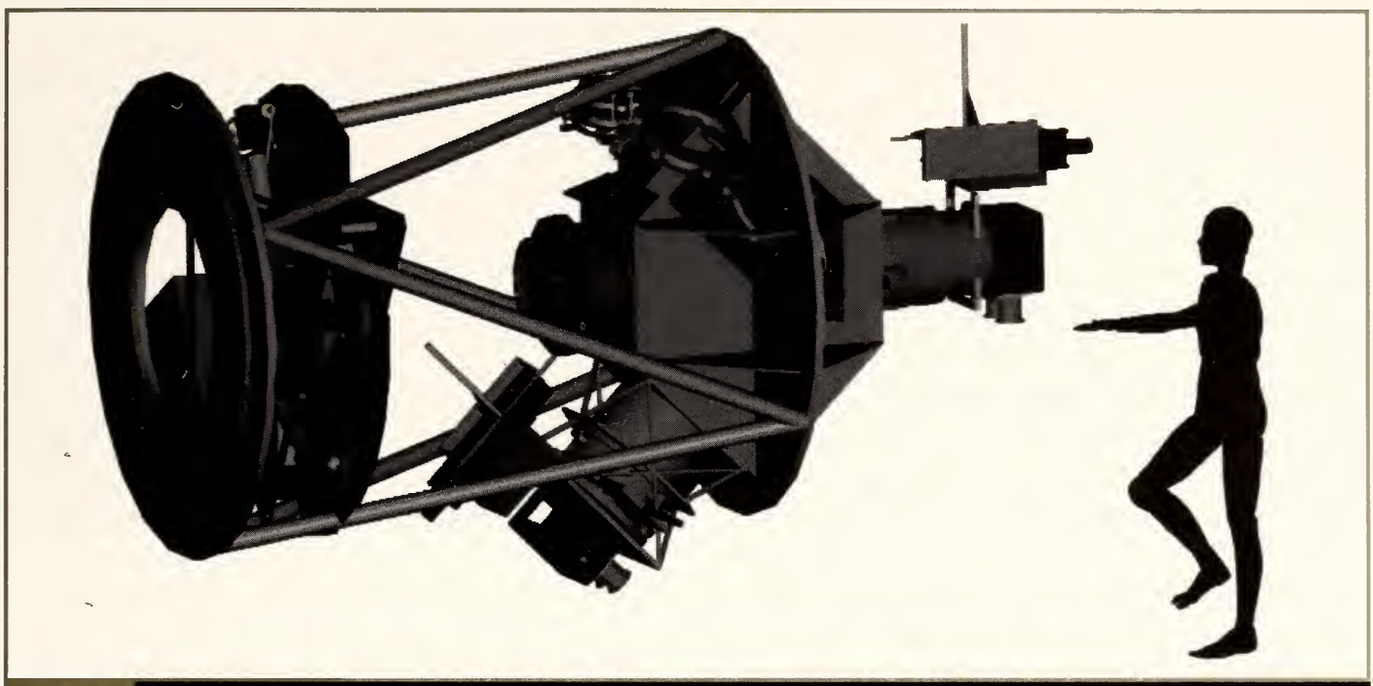


Fig. 1. This is a model of the Inamori Magellan Areal Camera and Spectrograph (IMACS) to be mounted on the Magellan I telescope. When complete, this wide-field instrument will be used in high-redshift studies of the universe.

The Postdoctoral Program

The research of the senior staff of the Observatories is described in the pages that follow. However, it is only part of the scientific activity on Santa Barbara Street. Another key component is the postdoctoral program. This program is the principal way in which the Observatories contribute to the education of young astronomers; but it does more than that. The constant flow of new faces and new ideas through the Observatories makes a significant contribution to the intellectual life of the department. It is a contribution to the future as well as to the present: the majority of Observatories Staff Members first came to Santa Barbara Street as postdocs.

There are usually about a dozen postdoctoral fellows and associates at the Observatories: three Carnegie Fellows, funded by the institution; up to three Hubble Fellows, funded by the Space Telescope Science Institute; and a half dozen postdoctoral associates, funded by grants to individual researchers. Unlike those in laboratory sciences such as biology, many astronomy postdocs are free agents. The Carnegie and Hubble Fellows, in particular, are completely independent researchers, doing the science they want to do in the way they want to do it. This is a great challenge as well as a great opportunity for a still-maturing scientist, and our fellows almost invariably make the most of the opportunity. Indeed, former Observatories postdocs have been extremely successful in their later careers and populate many of the leading astronomy positions.

Carnegie postdocs work on a wide variety of problems either on their own or in collaboration with Observatories staff. A few examples follow.

Carnegie Fellow Jason Prochaska uses the light from extremely distant quasi-stellar objects (QSOs) to probe the contents of the universe. The view of the universe normally provided by telescopes, whether optical, radio, or x-ray, is a biased one, because it is dominated by those objects that are copious emitters of optical, radio, or x-radiation. QSO light tells us about QSOs, of course, but it is also an unbiased probe of all the space through which the light travels on the way to our telescope. This probe reveals a very different universe, filled with gas, which leaves telltale absorption lines in the QSO spectrum. The challenge is to relate the objects detected by this technique to the luminous objects seen in usual observations. The strongest absorption lines are believed to be produced in the disks of young galaxies, but proof of this has been hard to find. Prochaska has used very high resolution spectroscopy of these systems to demonstrate that they are in ordered rotation, consistent with the hypothesis that they are indeed disk galaxies or, at the very least, rotating collapsing protogalaxies.

Another take on a somewhat later stage in galaxy evolution is provided by Carnegie Fellow Scott Trager's study of elliptical galaxies and spiral galaxy bulges. These are both spheroidal systems thought to be products of the earliest phase of galaxy formation. The spectrum of a collection of young (less than 1 billion years old) stars differs markedly from that of a collection of old (10 billion years old) stars. However, the differences between the spectra of 5 and 10-billion-year-old stellar populations are quite subtle. It is these small differences that Trager searches for. He has found that the bulges of spiral galaxies with big bulges (such as the Andromeda galaxy) are quite old, having formed very early in the history of the universe, while the bulges of at least some disk galaxies with small bulges are quite young—no older than their own disks. This suggests that the two types of spiral galaxies form in reverse order: the large bulges may form as elliptical galaxies and then accrete their disks, while small bulges may form from the disks themselves.

One can directly study the earlier history of elliptical galaxies by observing them at high redshifts. As Pat McCarthy and Eric Persson describe in following



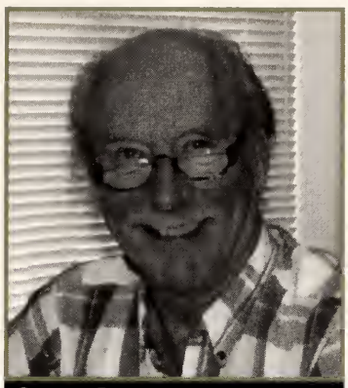
Fig. 2. The Andromeda galaxy M31.

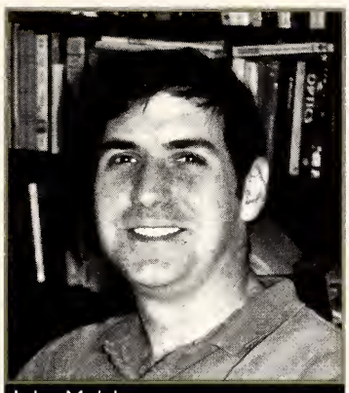
pages, high-redshift ellipticals are very red, and are most easily discovered using a combination of visible light and infrared observations. Persson, McCarthy, and Hubble Fellow Ron Marzke are leading Carnegie's participation in a collaborative project with the Institute of Astronomy at Cambridge University. This project mates an infrared detector system from Cambridge with an optical system produced by Persson's infrared instrumentation group to form the most powerful infrared survey instrument extant. Mounted on the du Pont telescope at Las Campanas, this instrument is producing the most extensive deep-infrared survey yet obtained. When combined with optical observations, these data will form the basis for Magellan telescope studies of early elliptical and starburst galaxies, and the evolution of clustering in the universe.

Department News

The Observatories continue to grow as scientific, technical, and support staff are added. Most of the growth has been driven by Magellan's need for instrument builders, programmers, operations staff, etc. Finding yet another unused basement space that can be turned into new offices has

become a constant preoccupation. Two new Staff Members were appointed during the past year to replace Allan Sandage and George Preston, who are both retiring. John Mulchaey received his Ph.D. in 1994 from the University of Maryland and has been a fellow at the Observatories ever since. He is a leader in the study of groups of galaxies, the most common but most neglected galactic environment. Mulchaey's work has revealed surprising new properties of groups of galaxies, including some in which all the galaxies have merged into one giant object.


George Preston


John Mulchaey.

Michael Rauch received his Ph.D. in 1993 from Cambridge University. He worked at the Observatories and at Caltech, and is now on the staff of the European Southern Observatory. Dr. Rauch's field is absorption-line QSOs. This is an area of long-standing importance for understanding the contents and structure of the universe; it has undergone a significant flowering in recent years due in significant part to Dr. Rauch's work. Unlike Prochaska's work in the same area, Rauch's focuses on the lowest-density systems, which are thought to be primordial gas clouds that have not yet condensed into bound systems.

Dr. Luis Ho began a five-year appointment as Staff Associate. Dr. Ho's principal interest is the incidence and properties of black holes in the centers of galaxies. Such black holes manifest themselves in two ways: by their gravitational pull on the surrounding stars, and by powering active galactic nuclei (AGNs). He has shown that such AGNs are much more prevalent than previously thought, suggesting that most, if not all, large galaxies harbor a supermassive black hole in their centers.

Another very welcome addition is Mark Phillips, who was appointed Associate Director of the Las Campanas Observatory. Dr. Phillips was a long-time staff member and former Associate Director of the Cerro Tololo Inter-American Observatory (CTIO) in La Serena, Chile, and he is a leading authority on supernovae. His calibration of the luminosities of supernovae is central to recent work using them as cosmological probes. He has moved across the street from CTIO to El Pino to continue his supernova research, and to work with LCO director Miguel Roth to manage the increasingly complex Las Campanas operation.

The Magellan Project

The enclosure and mount of the Magellan I telescope are essentially complete. Only minor additions to the telescope control system software remain. Work on the aluminization system continues; it is expected to be ready for a first coating of the primary mirror in the spring of 2000. Figuring was completed for the primary mirror at the Steward Observatory Mirror Laboratory (SOML) and for the f/11 secondary mirror at Contraves. Both mirrors are superb, meeting or exceeding specifications at all levels. Unfortunately, slow progress on the f/15 silicon carbine secondary mirror has forced a suspension of that effort. By mid-1999, the primary mirror support system (also being produced by SOML) was nearing completion, and the mirror and mirror cell were shipped to Chile in the fall of 1999.

Meanwhile, erection of the Magellan II enclosure has reached the halfway point. All steel for the fixed lower part of the enclosure is in place, but completion of the rotating upper half awaits delivery of the remaining steel from the fabricator in Spain. Assembly of the telescope mount is well under way at L&F Industries in Huntington Park, California. The Magellan II primary mirror was successfully cast in the fall of 1998 at SOML, and work on the back side of the mirror is nearly complete.

The IMACS spectrograph for Magellan I passed its preliminary design review in April 1999. Fabrication of the optics for the collimator and long camera, and fabrication of mechanical com-



Fig. 3. The Magellan Project's facilities at Las Campanas include the dome for the first telescope, as shown in the foreground. The enclosure for the Magellan II telescope is under construction in the background.

ponents should begin by the end of 1999. The mechanical design of the Kyocera Echelle Spectrograph is also near completion. Design work on the DDI infrared spectrograph continues, but progress has been slowed by the need to complete the infrared camera, described earlier, for the du Pont telescope. Most of the glass for the optics has been delivered, and polishing of elements should begin in the latter half of 1999.

—Augustus Oemler, Jr.

Alan Dressler

One of the great mysteries of modern astronomy is the nature, amount, and distribution of the dark matter that dominates the universe. A principal direction of Alan Dressler's research has been to try to map the distribution of dark matter on cosmic scales by tracing its presence through the gravitational pull it exerts on galaxies. By finding the "peculiar velocities" of thousands of galaxies in our cosmic neighborhood, Dressler and his colleagues discovered a huge concentration of dark matter, which they named the Great Attractor.



Alan Dressler

This year marked a milestone in the study. Data from the new technique called s*urface brightness fluctuations* have at last been brought to bear on the problem. Many of the new measurements were made with the du Pont CCD cameras and relied on the excellent observing conditions at Las Campanas Observatory. The data took almost 10 years to obtain, and provide the most accurate peculiar velocities to date. In three new papers, Dressler and his colleagues John Tonry of the University of Hawaii, John Blakeslee of Caltech, and Ed Ajhar of the National Optical Astronomy Observatories confirm the existence of the Great Attractor. Additionally, the researchers were able to see, for the first time, the weaker flows of galaxies into much smaller mass concentrations, as well as the flows away from voids—places where few galaxies are seen and the corresponding mass density is thought to be very low. The higher resolution and sensitivity of these new dark-matter maps will allow a much better determination of the extent to which the galaxy distribution traces the dark matter. This information is crucial to interpreting the large-scale structure of the universe as mapped by galaxies, and to understanding the role of dark matter in galaxy formation.

Another theme of Dressler's research involves the question of how galaxies formed and evolved over cosmic time. Astronomers have the unique ability to look back in time as they look far out into space. With their colleagues, Dressler and Gus Oemler have been using large ground-based telescopes and the Hubble Space Telescope to observe distant galaxies to determine their properties at earlier



Fig. 4. Observatories' postdoctoral fellows and associates (from left): Scott Trager, Scott Chapman, Lin Yan, Ben Weiner, Swara Ravindranath, Ron Marzke, and Jason Prochaska.

times. This collaboration, known as the MORPHS Project, has produced two major papers this year. The papers describe the connection between galaxy morphology (structure) and star-formation history in galaxies seen as they were 5 billion years ago. Among the conclusions of this work is that bursts of star formation were much more common in galaxies at that epoch, in contrast to the steadier star-formation rate characteristic of galaxies today. Additionally, the scientists found that because these starbursts were often shrouded by dust, their importance had been underestimated in earlier work.

The MORPHS study concluded that elliptical galaxies—the spheroidal systems that are most common in regions of high galaxy density—are generally old, nearly as old as the universe, but that over the last 5 billion years many spiral galaxies—disk galaxies with ongoing star formation—have been transformed to a dormant kind of disk galaxy called an S0. The specific mechanisms responsible for this change remain elusive and are still under study by the group.

Over the next two years Dressler will devote considerable effort as principal investigator of the IMACS instrument, a sensitive multiobject spectrograph and camera with a very wide field. When mated with the new Magellan I telescope, this instrumentation will open new territory in the high-redshift universe for Dressler and colleagues to study the evolution of galaxies with lookback time.

Wendy Freedman

Big Bang cosmology makes a number of predictions, one of which is the expansion of the universe. However, the Big Bang theory does not predict how fast that expansion is, or what the density of matter in the universe is. These quantities, which describe the fundamental, global nature of the universe, must be determined by observations. For the past 15 years, Wendy Freedman has been working on a project to measure the Hubble constant—the rate of the expansion of the universe. The Hubble constant, when combined with a value for the average density of mass/energy in the universe, yields a measure of the universe's age.

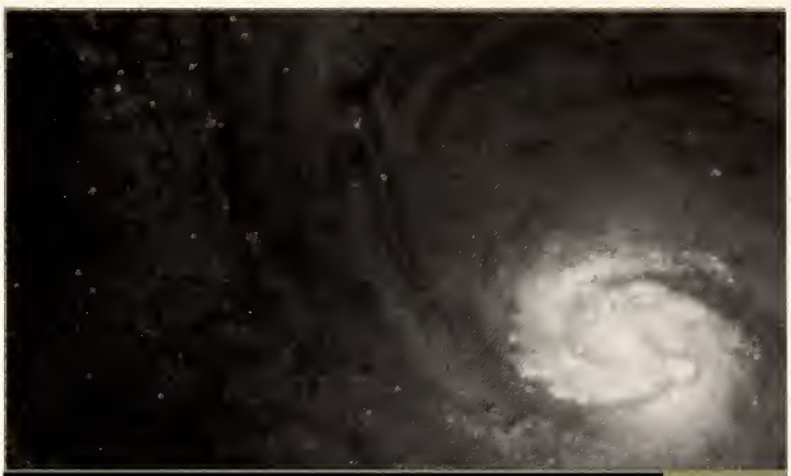


Fig. 5. The galaxy Messier 100 is shown here as imaged by the Hubble Space Telescope.

Freedman is a principal investigator, with Robert Kennicutt of the University of Arizona and Jeremy Mould of the Australian National University, of a group of 27 astronomers located across the U.S. and in Canada, Great Britain, and Australia. For the past eight years, the group has been using the Hubble Space Telescope (HST) to improve accuracy in the measurement of the Hubble constant. Most of the effort in the HST project has been aimed at measuring the distances to galaxies using a relation between the period and luminosity of Cepheid variables—pulsating stars that are used to measure distance. Turbulence in the Earth's atmosphere makes these measurements impossible from the ground for all but the nearest galaxies. As part of the Key Project, the team measured Cepheid distances to 18 galaxies and discovered about 750 Cepheid variables. Even with the HST, however, the range for discovery of Cepheids is limited to distances less than about 80 million light-years. To measure the Hubble constant, it is necessary to measure farther out. To do so, the scientists tied the Cepheid distances into other methods that are based on more luminous objects visible at greater distances, such as luminous supernovae, and spiral and elliptical galaxies.



Wendy Freedman

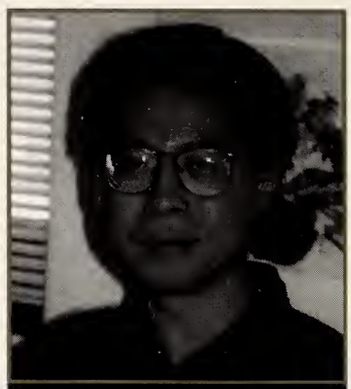
Using four independent methods, all calibrated by the new HST Cepheid distances, Freedman and collaborators found a value of the Hubble constant of 71 km/sec/megaparsec with a total uncertainty of 10%. The current best estimates for the average density of matter in the universe suggest a lower value than was previously thought; it is now believed to be about one quarter of the so-called critical density. This new value, when coupled with a Hubble constant of 71, yields a universe that is about 12 billion years old. This age agrees well with recent results from the *Hipparcos* satellite, which give very similar ages for the oldest stars in our galaxy.

Several years ago, the preferred theoretical models suggested that we live in a critical-density universe. Under that scenario, values of the Hubble constant of 70 or 80 led to a universe that is 8 or 9 billion years old. This result was in apparent conflict with the then-current estimates for the ages of globular clusters at 15 billion years. This paradox is very simply resolved, however, if we live in a low-matter density universe. We might still live in a universe at critical density (if there is another component of energy, perhaps due to the so-called cosmological constant), but the new Hubble constant results do not require this possibility.

Luis Ho

Luis Ho's arrival at the Observatories last fall coincided with a particularly eventful time, the birth of his son Hansun. After the inevitably hectic period of moving across the country, the transition to LA life was smooth. It did not take long for his wife, Sandra, and daughter Mya to appreciate the virtues of sunny southern California.

Ho's work primarily focuses on two themes: physical processes in galactic nuclei and the properties of young, massive extragalactic star clusters. The study of the central regions of nearby galaxies has entered an exciting era with the advent of powerful new instruments such as the Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope (HST). Ho and his collaborators are using STIS to obtain high-resolution, spatially resolved spectra of the nuclear regions of a large sample of galaxies. These data yield kinematic measurements of gas and stars, information that can constrain the central mass distribution in an unprecedentedly large number of galaxies, and thus verify the existence of massive black holes. The same data also give exquisite spectral information that allows Ho to probe the stellar population and gas properties on spatial scales of a few parsecs. Ho is also taking advantage of the fantastic imaging capability of the HST to study the structure of spiral galaxies' bulges. The HST data reveal a bewildering array of fine structures previously unknown from ground-based images such as spiral arms, dust lanes, star clusters, and compact nuclei.


Luis Ho

In an effort to better understand the physics of low-luminosity, active galactic nuclei (AGNs)—common in most large nearby galaxies—Ho has initiated a suite of observational programs using the HST, x-ray satellites, and ground-based radio telescopes. The goal of these programs is the same: to characterize the properties of nearby galactic nuclei at many wavelengths. These nuclei have been virtually unstudied because of their extreme faintness. The initial results are startling: the broadband spectral energy distributions of low-luminosity AGNs look remarkably different from those of the traditionally studied, high-power AGNs, such as Seyfert nuclei and quasars. This information strongly suggests a difference in the process by which the central black holes accrete matter in the two classes of AGNs; a suspicion confirmed by theoretical calculations made with colleagues at Harvard.

Ho recently started work in two rather different directions. With Mark Phillips and collaborators at Cerro Tololo Inter-American Observatory, Ho joined an ambitious study, which employs a large-format camera to monitor a large number of galaxies with redshifts up to 0.1. The primary objective is to search for local supernovae and to

characterize their properties as a function of their environment. Another objective is to search for flashes of light from galactic nuclei. These flashes are a unique signature predicted from the tidal disruption of stars caused by massive black holes, which are believed to be ubiquitous in galactic nuclei. With John Mulchaey, Gus Oemler, and Steve Shectman, Ho is also using the du Pont telescope at Las Campanas to obtain morphological data and integrated optical spectra of a large sample of "local" (redshifts less than 0.1) galaxies. The intention is to assemble a library of reference data to serve as a useful present-epoch benchmark for future optical studies of more distant galaxies.

William Kunkel

Kunkel's research has focused on the internal dynamics of the Large and Small Magellanic Clouds (moderate-size satellites of the Milky Way) using observations from the motion of carbon stars. Carbon stars were selected as test particles because of their age: they are old enough to have completely decoupled from the motions of the gas, and no longer retain traces from the earliest phases of galaxy formation. Because of these features, carbon star motion is expected to represent the median dynamic behavior under gravity alone. Up to now, astronomers have assumed that the motion of gas is a reliable tracer of gravitational forces. Kunkel, in collaboration with Serge Demers of the University of Montreal and Mike Irwin of the Royal Greenwich Observatory, discovered significant deviations between the stellar and gas motions in both Magellanic Clouds. The data acquisition phase of the study was completed in 1998, and 1999 has been dedicated to the final interpretive exercise.

The Magellanic Clouds are satellites on highly elongated orbits. They receive episodic impulses of mechanical energy generated by tidal forces each time they approach one another or the Milky Way. These tidal impulses offer an opportunity to "tweak" the behavior of gravity in a known way, facilitating specific tests that are easily replicated in a computer simulation. Comparison of the behavior seen in the numerical simulation with that observed in the carbon stars reveals serious difficulties with otherwise well-established tradition. The most serious problem is the distribution of dark matter. According to established lore, it is expected to follow gravitational forces exclusively, yet somehow sustain a spatial distribution different from that of observed matter, which congregates at the centers of dark matter complexes. Other conundrums addressed include the surprise that unlike carbon stars in the Milky Way, carbon stars in the Magellanic Clouds are found far from current sites of star formation. Large amounts of energy (and traditionally, a very long time) are required to carry carbon stars from their birth locations to where they are seen today. Mechanisms are thus needed to "stir things up," and tidal impulses are the outstanding candidates.

Since numerical simulations have clarified the global dynamic picture of gravitational processes in the Magellanic Clouds, the results of the present study indicate that significant nongravitational forces are acting on the gaseous components of the local satellites. Eventually, the significance of these findings is expected to impact how reliably one can trust the information about the spins in small galaxies, which is inferred from observations of rotating gas disks. More important, the findings will affect inferences about the distribution of gravitational potentials from such observations.

In the future, Kunkel intends to explore the gas/stars discrepancies in the nearest of the more remote galaxies: IC1613 and NGC6822. These are examples of systems experiencing occasional tidal impulses, and NGC3109 is one in which such impulses (stirring spoons!) are expected to be absent.

Patrick McCarthy

The stars that constitute the bulk of the mass of galaxies emit most of their luminous energy at wavelengths longer than 0.5 microns. These cool, giant stars have masses comparable to that of the Sun and lifetimes of billions of years. At large distances, the cosmological redshift has shifted this radiation to the near-infrared (IR). Most surveys of high-redshift galaxies have been confined to visible wavelengths, and thus sample ultraviolet (UV) photons

emitted at the source. The emitted and observed wavelengths are related by $\lambda_{emitted} = \lambda_{observed}/(1 + z)$, where z is the redshift. The ultraviolet luminosity of galaxies is often dominated by a small population of massive stars that produce 100 to 1,000 times more luminosity per unit mass than stars like the Sun, but have lifetimes that are measured in millions rather than billions of years. The UV luminosities of galaxies thus reflect their present star formation rates, while near-infrared luminosities are a far better tracer of the total stellar mass.

For the past few years Patrick McCarthy and colleagues have been applying near-infrared techniques, from Las Campanas and from orbit, to study faint and distant galaxies. Together with Staff Member Eric Persson and Hubble Fellow Ron Marzke, McCarthy has embarked on an ambitious survey of faint galaxies in the near-infrared. Using a unique camera containing a mosaic of four large near-IR detectors, the scientists are surveying an area of the sky four and a half times the area of the full Moon. This survey will yield a sample of between 2,000 and 4,000 old galaxies at large redshifts, and will allow the astronomers to precisely measure their spatial clustering—an important clue in understanding the growth of density irregularities in the early universe.



Fig. 6. This is a near-infrared and optical image of a cluster of galaxies with a redshift of nearly 1. The picture is a composite of images at 0.5, 0.8, and 1.6 microns. Old galaxies are strongly clustered around the central object, a luminous radio source. These data were obtained with the du Pont telescope at Las Campanas.

Spectroscopy in the near-infrared offers a new window on galaxies at large redshifts. McCarthy and postdoctoral associate Lin Yan have used the near-IR spectrometer on board the Hubble Space Telescope to measure the star formation rates of galaxies with redshifts between 1 and 2. Yan and others find that the star formation rate at a redshift of 1.5 is 17 times larger than the present rate. This high rate of star formation is a factor of two to three times greater than the rate derived from ultraviolet measurements and implies that roughly 50% of the stars in the present universe were formed as recently as 5 billion years ago. This is in stark contrast to the very inactive and old galaxies that are the targets of the survey described above. These results highlight the fact that galaxy evolution is not a uniform or homogeneous process. The life history of a galaxy is greatly influenced by the environment in which it begins. Some reach maturity early in the history of the universe, while others lie dormant until some stimulus drives the conversion of gas into stars.

Andrew McWilliam

Andrew McWilliam's research focuses on nucleogenesis and galactic chemical evolution. His goal is to understand where and how the elements were produced by studying the composition of very old stars and stars born in different environments.

Stars produce most of the elements in the universe; supernovae (SNe) are particularly important sources. Theoretical models of SNe and other astrophysical enrichment events are very crude and require observational constraint. Stars of low mass are very long-lived and span the age of our galaxy. Such fossil stars can be used to trace the history of chemical evolution. In general, the oldest stars are the most metal-poor because fewer supernovae had occurred before the very early epoch when the stars formed.

Most stars contain the chemical signatures of many supernovae (over 100 million SNe have occurred in our galaxy), so the amplitude of abundance variations from individual SNe are usually insignificant. The abundance variations of individual SNe are more evident in stars composed of ejecta from only one or a few supernovae. These

stars are very metal poor and very rare. They show large abundance variations, some with detectable amounts of the radioactive element thorium, which can be used to measure the age of the galaxy. In 1998 and 1999, there were two searches for extremely metal-poor stars. Staff Members George Preston, Ian Thompson, and McWilliam conducted the first search toward the galactic bulge; the second was done by McWilliam in metal-poor dwarf spheroidal galaxies (dSph). At present, stars with metal abundances near 10^{-3} those of the Sun are confirmed, and two candidates near abundances of 10^{-4} solar have been identified.

McWilliam and Director Emeritus Leonard Searle have produced a model of stochastic chemical evolution to understand the 300-fold dispersion of strontium abundance in extremely metal-poor stars. The model assumes a distribution of supernovae Sr/Fe ratios from the most metal-poor stars; the ratios are selected randomly from this distribution and then mixed. Figure 7 shows predicted and observed abundances; note the excellent fit. The unusual position of two stars with metal abundances near 10^{-4} solar constrain the model, and suggest that stars composed of material from individual supernovae have metal abundances near $10^{-3.2}$ of the Sun.

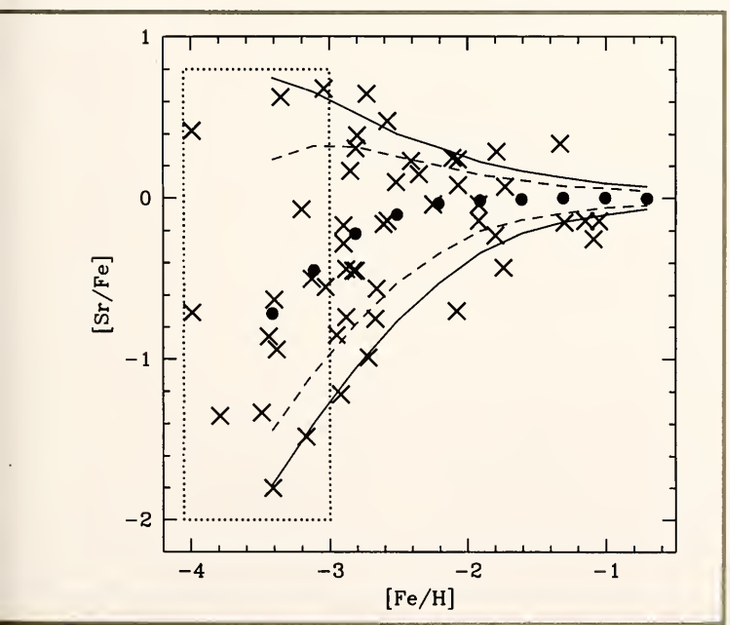


Fig. 7. The figure shows the observed abundances of Sr/Fe (crosses) compared with predictions. The region bounded by the dotted lines indicates the stars used to set the initial distribution in Sr/Fe ratio, while solid lines show the predicted evolution (5, 15, 85 and 95 percentiles) of Sr/Fe. Filled circles indicate the predicted evolution of the median Sr/Fe ratio.

The compositions of other environments permit tests of the chemical evolution paradigm. To this end, McWilliam and Tammy Smecker-Hane of UCI used the Keck telescope to acquire spectra of red giant stars in the Sagittarius dSph. The results show a large spread in metallicity and unusual abundances of O, Mg, Si, Ca, Al, and Na. One explanation for this spread is that the Sagittarius dSph experienced an extended quiescent period of several billion years followed by a burst of star formation, with the composition of the metal-rich population coming from metal-poor (10^{-2} of solar) type Ia supernovae.

McWilliam acquired CTIO spectra of 70 galactic-bulge red giants, and 12 spectra using the Keck I with Mike Rich of UCLA. The scientists found unusual enhancements of O and Eu at solar metallicity. These elements are mostly made by type II SNe (with short progenitor lifetimes), which indicates a rapid formation timescale for the galactic bulge on the order of one billion years. It is remarkable that the bulge reached solar metallicity so quickly.

Eric Persson

Recent rapid improvements in the quality and size of near-infrared imaging array detectors have led to significant advances in several areas of astronomy. Persson is leading a group of Carnegie scientists and engineers in the development of telescope instrumentation that exploits these new devices. They have built one wide-field survey camera for the du Pont 2.5-m telescope, and are currently designing infrared instruments for the two Magellan 6.5-m telescopes at Las Campanas. The group has started a number of projects with the new camera, the most demanding of which concerns the discovery, measurement, and follow-up spectroscopy on distant galaxies—particularly those whose properties and remote distances are such that they can only be studied at near-infrared wavelengths.

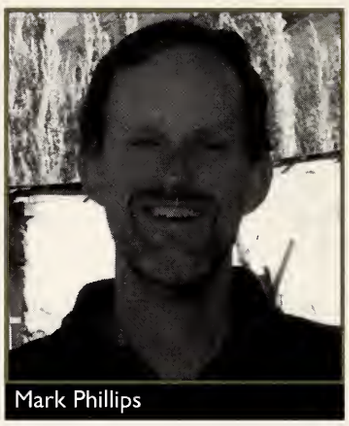
Until recently, it has been difficult to find significant numbers of these galaxies. This is solely due to technical reasons: detectors and cameras have not been large enough to cover large areas of sky. For the next several years, the Persson group will survey

one square degree of sky to find and accurately measure the brightnesses of thousands of high-redshift galaxies. It will then be possible to estimate their distances and intrinsic luminosities, and study their clustering tendencies in space. Another objective of the survey is to discover large numbers of abnormal galaxies that exist at great distances. Persson and others have serendipitously found distant galaxies that emit virtually all of their energy in the infrared range. While these galaxies are fairly easy to detect in the near-infrared, they can be completely invisible in the deepest optical searches. They are so rare that prohibitively large areas of sky must be surveyed to find new examples. Preliminary spectroscopic evidence on a handful of such galaxies indicates a heterogeneous population: some are likely to be intense star-forming galaxies buried within optically opaque dust clouds, while others appear to be passively evolving objects in which star formation ceased several billion years before. These objects will be prime targets for Magellan instrumentation.

For the past 70 years, astronomers have tried to determine the distance scale of the universe. Persson and Carnegie collaborators hope to advance this field by studying newly found type Ia supernovae. These objects are widely believed to provide the key to understanding how the timescale, geometry, and mass content of the universe can be reconciled within the framework of general relativity. Type Ia supernovae are stellar explosion events, which appear to follow a well-defined development of brightness over time as they rise to a maximum luminosity and then decline. Because the intrinsic luminosities of supernovae at maximum light are essentially the same event-to-event, relative distances to their remote counterparts, observed in host galaxies billions of light years away, can be determined in a fairly straightforward manner. However, it is vital to be certain that the local supernova events are physically the same as their distant counterparts. At near-infrared wavelengths, type Ia supernova light curves appear to be very similar to one another. With the new infrared camera on the 2.5-m telescope, Persson's group will monitor the many new supernovae found each year and create a database that will calibrate distances to the remote objects.

MARK PHILLIPS

Supernovae are among the most violent and energetic phenomena observed in the universe. The high temperatures reached inside a supernova explosion energize a wide range of nuclear reactions, which synthesize new heavy elements. These elements are then dispersed into interstellar space along with the products of the fusion reactions that originally powered the progenitor star.


Mark Phillips

The shock wave produced by a supernova can trigger the collapse of neighboring molecular clouds, leading to the formation of new stars. Some of these new stars will eventually end their lives as supernovae. This alternating cycle of the birth and death of stars has led to the steady heavy-element enrichment of the universe, making possible life as we know it on Earth.

Because of their extreme brightness at maximum, supernovae are potentially powerful "standard candles" for probing the geometry and expansion of the universe. The type Ia supernovae, which are thought to be the complete thermonuclear disruption of a small, very dense stellar remnant called a white dwarf, are especially attractive candidates. They display a high degree of homogeneity and can be observed to very great distances because of their immense luminosities at maximum light (up to 10 billion times that of the Sun).

Since the early 1980s, Mark Phillips has carried out observations of supernovae to understand in more detail the nature of these events and to calibrate their usage as standard candles. Several years ago, Phillips showed that the peak luminosities of the type Ia supernovae were not identical, but that these objects could still be used as standard candles because the luminosity of each event was correlated with the rate of decline from maximum light, which could be measured independently. Calibrating the exact dependence of this correlation has required obtaining precise light curves for

a large number of supernovae. In addition, a method had to be devised for deriving the absorption of the light of each supernova due to dust in its "host" galaxy. Phillips and his collaborators developed a technique for measuring this absorption, which then allowed them to correct the observed peak brightness of the supernova for this "missing" light. From this work, Phillips and his collaborators have been able to determine a value of the Hubble constant (a measure of the present rate of expansion of the universe) of approximately 65 km/sec/megaparsec.

Phillips has also been heavily involved in the effort to detect very distant supernovae. Using the Hubble Space Telescope, he and his collaborators recently demonstrated the feasibility of detecting supernovae at redshifts as great as $z = 1.5$, when the universe was only one-third its present age. In the future, it should be possible to probe the star-formation history of the universe by carrying out comprehensive searches for such distant supernovae.

Phillips and his collaborators are also using very distant type Ia supernovae to measure the expansion rate of the universe at earlier epochs. These observations have led to a surprising result: we seem to be living in an accelerating universe. Although unexpected, this finding has a certain attraction since it leads to an age of the universe that is consistent with the ages of the oldest stars in our galaxy. Nevertheless, these observations are sensitive to the possibility that the luminosities of the type Ia supernovae have evolved with time. During the next few years, Phillips plans to focus his research on testing the latter prospect through systematic observations of supernovae at a variety of redshifts and environments.

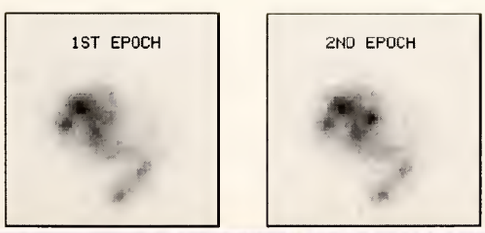


Fig. 8. These are images of the $z = 0.95$ galaxy 3-221.0 in the Hubble Deep Field. The first epoch image was taken in December 1995; the second epoch image was obtained two years later in December 1997. Note the appearance of a supernova in the second epoch image.

George Preston

George Preston, with Carnegie collaborators Andrew McWilliam, Stephen Shectman, and Ian Thompson, is engaged in the astronomical equivalent of looking for radium in pitchblende. He is searching for extremely rare astronomical relics—the earliest generations of stars formed in the Milky Way. The signature of these relics is the virtual absence of elements heavier than helium in their atmospheres. They are identified by wholesale examination of spectra from the myriad of stars that inhabit the dense central bulge of our galaxy.

The very first generation of stars was made of Big Bang material, that is, hydrogen and helium with a trace of lithium. All the heavier elements have been produced by nucleosynthesis in massive stars that explode as supernovae after they exhaust their fuel supplies. Debris from the first supernova explosions polluted the galactic gas. Out of this gas, future generations of stars formed. Continual repetition of this process for the past 15 billion years or so has gradually increased the heavy-element content of the universe to its present level.

The second generation of stars contained no more than one-tenth of a percent of the metal content of the Sun. These stars comprise no more than one-tenth of a percent of the stars formed since the beginning of time. These are the objects sought by the Carnegie team. Because they are made of gas enriched by single, or at most a few, supernova events, their chemical compositions tell what particular combinations of heavy elements are produced in various supernova explosions. What little was learned about the "yields" of supernovae from an earlier Carnegie survey reveals that these explosions are not all alike. Their debris exhibits enormous variety, which means that the accumulation of all the chemical elements to their present levels is a complex process of which we have only a dim comprehension.

The Carnegie team conducted the first phase of their new search for extremely metal-poor stars in

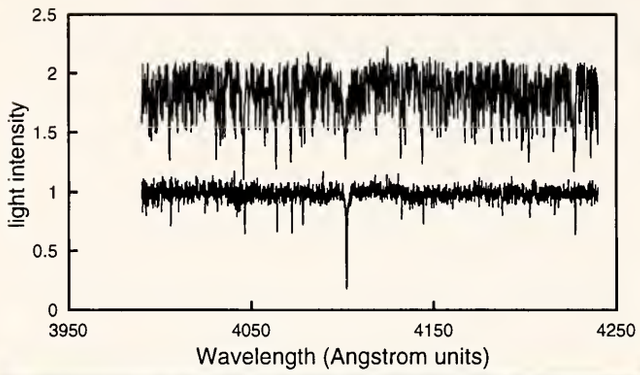


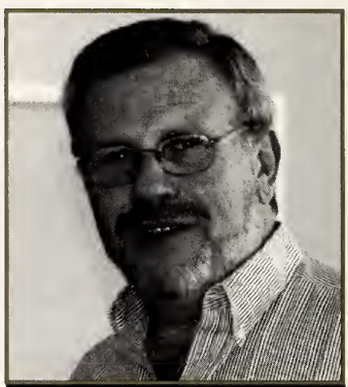
Fig. 9. This image shows spectra (plots of light intensity versus color progressing from blue to red) for two stars. The spectrum of the Sun with present-day levels of heavy elements (above) looks like a picket fence. The spectrum of CD -38:245, a star of similar temperature but with 10,000 times fewer heavy elements (below), looks almost featureless. Such stars are rare but unmistakable.

1997 and 1998 at Las Campanas using the Swope and du Pont telescopes. They performed CCD photometry in 50 star fields in the galactic bulge with a special set of filters that identify metal-poor candidates among the 100,000 red giants present. Unfortunately, the metal-poor signature can be forged by a few other exotic groups of stars—those with very high velocities, powerful chromospheric emission, or large carbon excesses. GRISM[1] spectroscopy of the metal-poor candidates initiated at the du Pont telescope in 1999, however, eliminated the forgers to produce a list of bona fide metal-poor stars. "We don't even know where the carbon in our bones came from," says Preston. He expects that in the next decade spectral analysis of these extremely metal-poor stars at the Magellan telescopes will shed light on this and many other questions about the creation and evolution of the chemical elements in the universe—and in our bones.

Miguel Roth

The interstellar medium contains all of the components from which stars are formed. It changes continuously as stars evolve and return part of the processed material to the medium. There are two particularly interesting phenomena in the processing of the interstellar medium: supernovae explosions and planetary nebulae (PN). Both phenomena, particularly the supernovae explosions, are sources of heavy elements.

Over the past five years, Roth has been involved in the study of "old" PNs. These nebulae arise from stars of intermediate mass that, during their evolution, expel an important fraction of their mass. The material that surrounds the evolved and very hot star at the core of the PN contains several distinctive elements, in particular, hydrogen, nitrogen, and oxygen.


Miguel Roth

PNs display a great variety of shapes; old ones tend to be rather spherical, with the star displaced from the geometrical center. This shape is indicative of the interaction of the PN with the medium that surrounds it. Spectroscopic determinations of the relative abundance of the elements H, N, and O can be correlated with optical and infrared images to understand the mechanisms involved in the origin and evolution of these objects.

A comparable scenario can be pictured when studying the evolution of the much more energetic expansion of material from supernovae explosions. Roth has looked at the interaction of some supernova remnants with the interstellar medium. In these cases, radio techniques were used to study the "clumpy" distribution of molecular species such as CO and H_2. When these data were correlated with tracers of star formation, the possibility of induced star formation became apparent. This may well be one of the mechanisms that trigger the formation of new generations of stars. Our Sun was formed as a consequence of such an explosion.

Sequential star formation is also probably present in areas surrounding what are known as HII regions. In some cases, very massive and short-lived stars ionize their surrounding medium and compress it as the HII region expands. Analysis of infrared images obtained at Las Campanas and

1 A GRISM is a special combination of diffraction Grating and pRISM used to analyze starlight.

images obtained with the Hubble Space Telescope confirmed the existence of a new generation of very young stars in the surroundings of a massive cluster known as R136. This cluster is located in the Tarantula Nebula, in the Large Magellanic Cloud.

Roth is collaborating with Mark Phillips (see above) to study the evolution of light curves of supernovae in infrared light. Using the evolution of the light curve, it is possible to determine accurately the peak luminosity of supernovae (Phillips Law). This information will allow the researchers to determine the distance to the host galaxies of these objects and the rate of expansion of the universe.

Infrared measurements have been mentioned several times in this essay. Accurate determinations of the luminosities of astronomical objects require the use of what are known as standard stars. It was necessary to establish a reliable list of such standards—rather tedious but fundamental work. Astronomers at Las Campanas devoted many nights to the systematic measurement of a body of such new stars, and researchers all over the world now use these standards.

Stephen Shectman

During the past year, Stephen Shectman spent five months in residence at the Las Campanas Observatory working on the control system for the Magellan I telescope. This work was conducted in collaboration with many members of the Magellan Project staff, particularly Joe Asa, Greg Bredthauer, Dave Carr, Emilio Cerda, Charlie Hull, Matt Johns, and Frank Perez.

There are several highlights from the control system work. For instance, the precision optical tape encoders were installed; they provide accurate information about the position of the telescope axes. The servomotor drives and amplifiers were brought into reliable operation, and accurate servo control of the telescope mount was implemented. When the telescope is tracking the position of a star, the telescope's motion is controlled to an accuracy of a few hundredths of an arcsecond. In order to achieve this precision, the positions of the large structural components of the telescope mount must be maintained to within about 1 micron.

An accurate time-base, using signals from the Global Positioning System, was also installed in the system. A small telescope and TV camera were attached to the side of the mount, and a map of pointing corrections was derived by measuring more than 100 star positions around the sky. These corrections were needed for the manufacturing tolerances and mechanical flexure of the telescope structure, which are many times greater than the allowable uncertainties in the telescope's positioning. The computer control system uses the pointing corrections to set the telescope to within a few arcseconds of any position on the sky. The telescope mount and its control system are now reliable enough and safe enough to allow the primary mirror and cell to be installed.

Shectman has also been working with Hubble Fellow Rebecca Bernstein on the construction of MIKE, the high-resolution optical spectrograph for Magellan. This spectrograph features separate optical paths for the red and blue parts of the spectrum. These permit the optical design, dispersing elements, antireflection coatings, and detectors to be optimized separately for the red and the blue. The spectrograph will be able to measure the entire optical spectrum of an object between 3,300 and 10,000 angstroms in a single observation, with a resolution of a few tenths of an angstrom.

During the past year, Shectman and Bernstein finalized the optical design of the spectrograph, ordered and received all of the optical glass, and sent the first components to the optical contractor for polishing. They also worked with consulting engineer Steve Gunnels to define the mechanical structure of the device.

Working with engineers from L&F Industries, Shectman also conducted a design study for a major modification of the 2.5-m du Pont telescope at Las Campanas. This modification would add a Newtonian focus and corrector to the top end of the telescope, where a mosaic CCD camera could be used to image a one-square-degree-area of the sky. This area is more than six times larger than

can be observed with a comparable mosaic camera at the present Cassegrain focus. Such a wide-field camera would be particularly interesting for conducting wide-area photometric surveys as well as real-time searches for distant supernovae, gravitational lens events, and variable stars. These examples require massive computational power, which has only recently become available and affordable.

Ian Thompson

The distances and ages of globular clusters—spherical systems consisting of upwards of 100,000 stars in our galaxy—are key stepping-stones on the path to understanding the age and scale of the universe. Globular clusters are among the oldest components of our galaxy. Previous measurements of the distances to them have compared the characteristics of different types of stars found in our solar neighborhood (for which we can estimate distances) with the same types of stars found in the clusters. For various reasons, measurements of the globular cluster distances suffer from systematic errors and remain the limiting factor in determining the ages of these objects.


Ian Thompson

Ian Thompson, with colleagues at the Observatories and the University of Warsaw, has a different approach to this distance problem. Observations of detached eclipsing binary stars allow a geometric measurement of distances. These systems are composed of two separated stars that orbit about each other, with the orbital plane in the line of sight to the stars. As one star passes in front of the other, the total light is modulated. Analysis of the shapes of these eclipses permits a measurement of the relative sizes of the stars and their separation. After additional observations are made of the variations of the radial velocities of the two stars, the absolute dimensions of the system can be derived from a simple application of Kepler's laws of gravity. Once the absolute sizes of the individual stars in the binary are known, the distance to the system can be measured by comparing the apparent brightness of the stars to their surface brightness as estimated from the infrared colors.

Thompson is searching for these exceedingly rare stars using the Swope 1-m telescope to monitor a selection of nearby southern globular clusters. Many nights of continuous monitoring are needed to detect the eclipses and then measure their orbital periods. Detailed measurements of the shape of the light curves are made with the du Pont 2.5-m telescope. When the Magellan telescopes are operational, the radial velocity curves will be measured with the echelle spectrograph. Although only one or two eclipsing binaries are expected to be detected in each cluster, these will be sufficient to overhaul our imperfect knowledge of their distances and ages. This research, and the collaboration with George Preston, Andrew McWilliam, and Steve Shectman in the search for extremely metal-poor stars, will show the new way in which the smaller telescopes at Las Campanas will be used in the upcoming Magellan era. Resources will be devoted to extensive surveys for interesting objects that can be studied in greater detail with the twin telescopes.

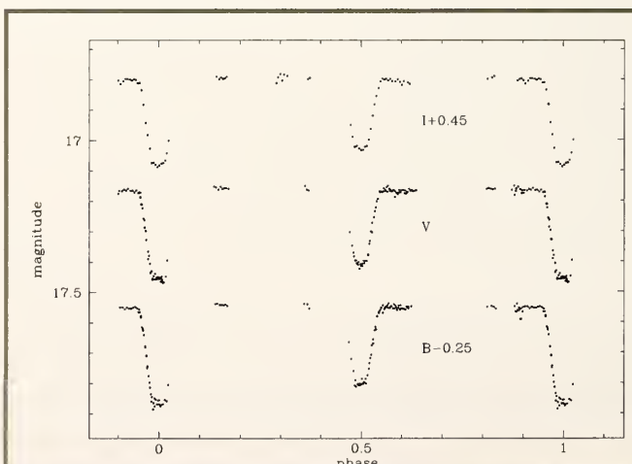


Fig. 10. This image shows light curves of a detached eclipsing binary in the globular cluster Omega Centauri, as measured in the blue, visual, and near-infrared. The eclipses occur at phases 0.0 and 0.5, and the different depths of the eclipses indicate that the two stars in the binary are not equally bright.

Ray Weymann

Much of Ray Weymann's time during the past year was devoted to organizing, convening, and editing the proceedings of a workshop entitled "Photometric Redshifts and High Redshift Galaxies." The event was held in the William T. Golden Auditorium at the Observatories in Pasadena during April 28-30, 1999. Stimulated by research using the Space Telescope NICMOS camera (described below), the workshop was attended by about 65 astronomers from the U.S. and abroad. Photometric redshifts use direct images of galaxies taken in several bandpasses to estimate the redshift, or distance, of galaxies. The virtues of this technique are that it can produce redshifts of huge numbers of galaxies much more efficiently (in terms of telescope time), and it can view the bodies to much fainter brightness levels than can the more accurate method of measuring galaxy spectra with large telescopes. A closely related topic that was addressed involves the search for extremely distant galaxies to trace the history of star and galaxy formation in the very early phase of the expanding universe. The proceedings of the workshop are in volume 191 of the Astronomical Society of the Pacific Conference Series published in late November. Lisa Storrie-Lombardi, formerly of the Observatories and now at Caltech, and Robert Brunner and Marcin Sawicki (also of Caltech) collaborated with Weymann to organize the workshop.



Ray Weymann

The impetus for the workshop came from research using observations with the infrared NICMOS camera on the Hubble Space Telescope. The observations, combined with previous visible light observations in the Hubble Deep Field, provided a set of images ideally suited for both the determination of photometric redshifts and the search for a very high redshift galaxy. This search yielded one galaxy that was confirmed to have a redshift of $z = 5.6$ based on spectroscopic observations made with the Keck telescope. The images that identified this as a likely candidate for a very high redshift galaxy are shown in Fig. 11. The main goal of the current research is to see whether, and how well, astronomers can estimate both the redshift of the galaxies using the photometric redshift technique and simultaneously estimate the internal dust absorption of the ultraviolet light associated with stars being formed in the galaxy or protogalaxy. It has recently become apparent that correction for this absorption is crucial to obtaining a true picture of the rate at which stars have been forming in the history of the universe. This is far more difficult than estimating only the redshift since the colors of a galaxy undergoing a vigorous burst of star formation, coupled with moderately heavy dust absorption, closely mimics the colors of a galaxy with only moderate star-formation rates and little or no dust absorption.

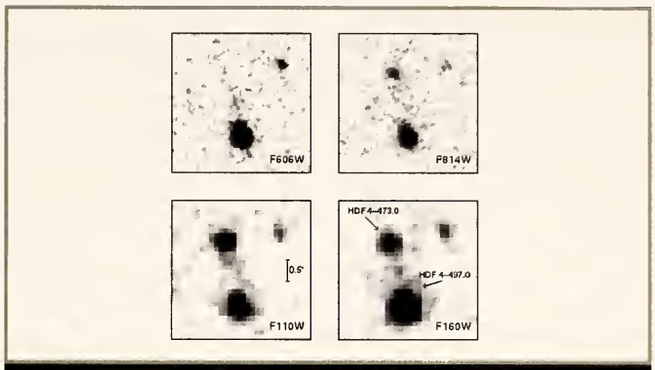


Fig. 11. These are Hubble Space Telescope images of a galaxy at a redshift of 5.6. The images labeled F606W and F814W were taken with a visible light CCD camera, and those labeled F110W and F160W were taken with the infrared NICMOS camera. The galaxy, labeled HDF 4-473.0, is relatively bright in the two infrared images, much fainter in the F814W image, and invisible in the shortest-wavelength image, F606W. The brightness ratio of these images has a distinctive signature indicative of a high-redshift star-forming protogalaxy and illustrates the use of the photometric redshift technique. The redshift of this very distant object was confirmed using the Keck telescope on Mauna Kea after several hours of exposure.

In a different field of extragalactic astronomy, Weymann is analyzing data on a bright quasar taken with the new STIS spectrograph on the Hubble Space Telescope. He will compare the properties of intergalactic hydrogen gas clouds and their association with galaxies with the predictions from computer simulations of the evolving universe. These data are being augmented by spectroscopic redshifts of galaxies close to the quasar (in angle, not distance) observed with the 2.5-m du Pont telescope.

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July 1, 1998 – June 30, 1999

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Wendy Freedman
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Andrew McWilliam
Augustus Oemler, Jr., *Director*
Eric Persson
George Preston
Allan Sandage, *Emeritus Staff Member*
Leonard Searle, *Director Emeritus*
Stephen Shectman
Ian Thompson
Ray Weymann

Senior Research Associate

Luis Ho[1]

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Rebecca Bernstein, *Hubble Fellow*[3]
Scott Chapman, *Magellan Instrumentation Fellow*[4]
Julianne Dalcanton, *Fellow*[5]
Carme Gallart, *Research Fellow*[6]
Mauro Giavalisco, *Hubble Fellow*[6]
Ron Marzke, *Hubble Fellow*
John Mulchaey, *Fellow*
Jason Prochaska, *Carnegie Fellow*[7]
Lisa Storrie-Lombardi, *Research Associate*
Scott Trager, *Starr Fellow*
Ben Weiner, *McClintock Fellow*
Lin Yan, *Research Associate*

Predoctoral Fellow

Yasuhiro Hashimoto, *Predoctoral Fellow*

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Mark Phillips, *Associate Director, Las Campanas Observatory*[8]
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Las Campanas Fellow

Gaspar Galaz, *Andes/Carnegie Fellow*

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Greg Burley, *Instrument Scientist*
David Murphy, *Instrument Scientist*
Brian Sutin, *Optical Scientist*

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John Grula, *Head Librarian, Information Services/Publications Manager*
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Robert Mejia, *Housekeeper*
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Jeanette Stone, *Purchasing Manager*
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Richard Sumock, *Instrument Maker*[14]
Estuardo Vasquez, *Instrument Maker*
Steven K. Wilson, *Facilities Manager*

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Juan Jeraldo, *Chef*
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Edgardo Costa, *University of Chile*
Vandana Desai, *University of Washington*
Richard Ellis, *Cambridge University*
Andrew Firth, *Cambridge University*
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Richard McMahon, *Cambridge University*
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Richard Patterson, *University of Virginia*
Isabel Perez, *University of Chile*
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Grzegorz Pojmanski, *Warsaw University*
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Paul Weissman, *Jet Propulsion Laboratory*
Josh Winn, *Massachusetts Institute of Technology*
Ann Zabludoff, *University of California at Santa Cruz*
Dennis Zaritsky, *University of California at Santa Cruz*

[1]From August 10, 1998
[2]From October 10, 1998
[3]From November 1, 1998
[4]From June 1, 1999
[5]To August 31, 1998
[6]To December 31, 1998
[7]From September 1, 1998
[8]From July 1, 1998
[9]Deceased February 5, 1999
[10]From October 5, 1998
[11]Retired June 30, 1999
[12]From April 1, 1999
[13]To August 31, 1999
[14]From December 1, 1998
[15]From September 28, 1998
[16]To September 10, 1998
[17]To September 30, 1998

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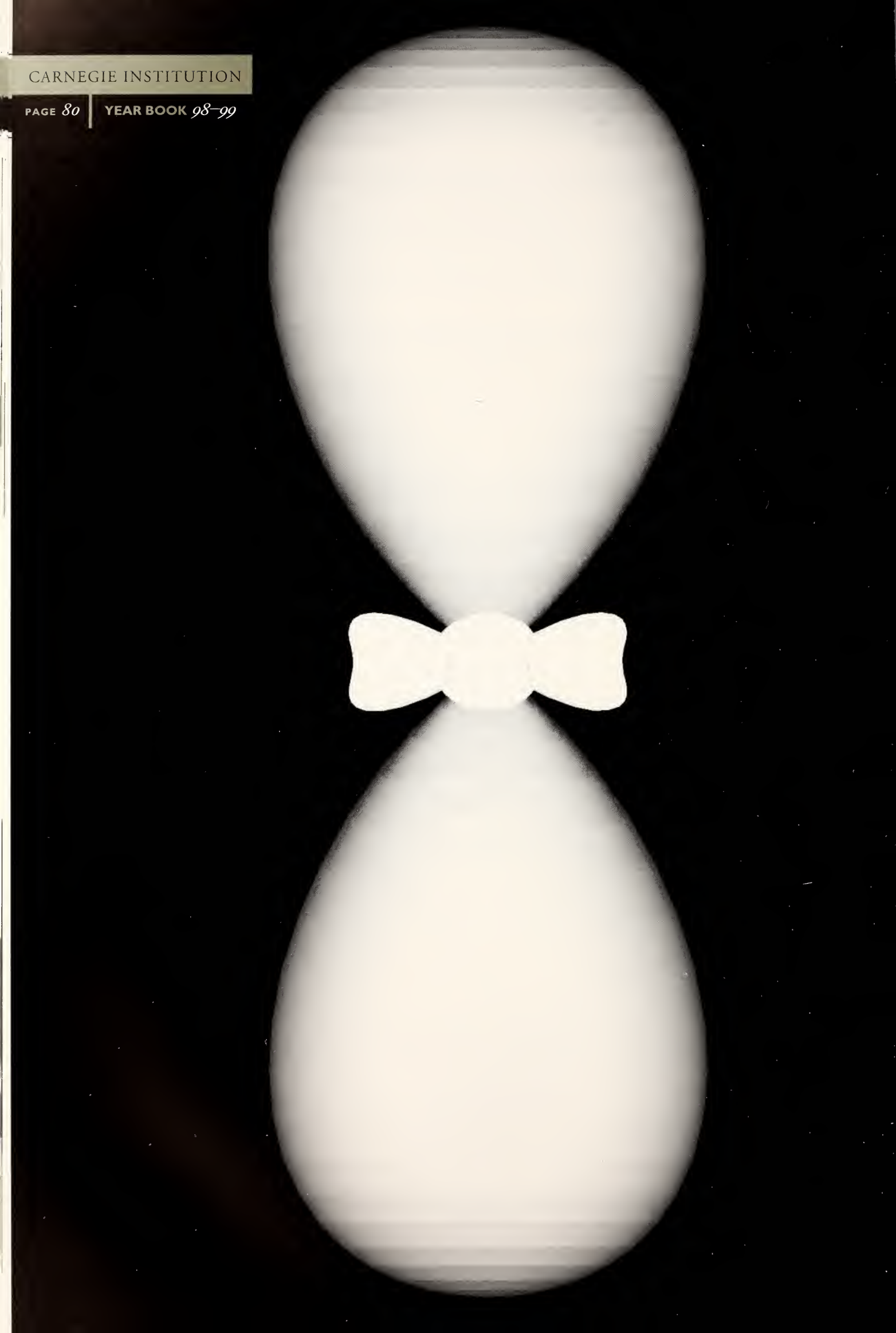
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THE DIRECTOR'S INTRODUCTION

"THERE IS FERTILE GROUND IN THE SEAMS BETWEEN THE TRADITIONAL DISCIPLINES WHERE THE NEW DISCOVERIES ARE TAKING PLACE."

Since its inception in 1905, the Geophysical Laboratory (GL) has been one of the world's foremost laboratories in the science of petrology—the study of rocks. GL scientists are renowned for their research into the formation and evolution of terrestrial rocks. A major goal of this science has been to understand the physics and chemistry of the Earth's deep interior. Toward this end, the lab has remained at the forefront of high-pressure and high-temperature research.

GL has pioneered many laboratory methods in high-pressure research. The advent of the diamond-anvil pressure cell in the 1960s, and its development since, has been a hallmark of this work. Over the years, many new methods and instruments have been developed to improve the cell's ability to measure the physical and chemical properties of materials and the transformations they undergo with changing pressure and temperature. As a result, unsuspected phenomena of fundamental, condensed matter have been discovered and have been applied to problems in understanding the interiors of the Earth, Mars, and the gas giant planets such as Jupiter.

With GL's global reputation in high-pressure physical science, this research area continues to grow steadily under the leadership of Dave Mao, Rus Hemley, and the lab's last director, Charles Prewitt. This growth was accelerated nine years ago with the establishment, by the National Science Foundation (NSF), of the Center for High Pressure Research. The Geophysical Lab is a member of a consortium that includes the State University of New York (SUNY) Stony Brook, UC Davis, and UC San Diego. A critical part of the consortium's work is the use of the second-generation x-ray synchrotron source at Brookhaven National Laboratory.

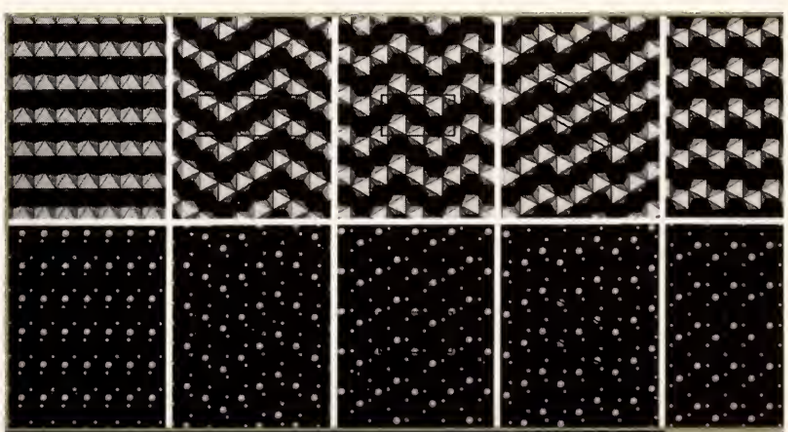


Fig. 1. This computer model reveals the predicted structures, under high pressure, of common beach sand—silica. (Courtesy Russell Hemley and David Teter)

Left: Fu and Cohen presented a model for understanding the huge electromechanical coupling in new single-crystal piezoelectrics. They tested the model by studying $BaTiO_3$, a classic ferroelectric. The figure opposite is a 3-D polar plot that shows the computed c-axis strain as a function of polarization direction in $BaTiO_3$. The bow-shaped area is negative. Large strains can be obtained by rotating the polarization direction. (Image courtesy Ronald Cohen.)

The NSF funded the center for a limited, 11-year period. The vision now is to establish a long-term center at GL. The staff would consist of mineral physicists, petrologists, physicists, and chemists. They would use laboratories and computers at GL and leverage costly national facilities at Argonne National Laboratory and Brookhaven to investigate materials at ever increasing pressures. Toward this end, a new high-pressure collaborative access team has just been formed, under the direction of Dave Mao, to build and operate a new dedicated beamline facility for high-pressure x-ray materials science at the third-generation Advanced Photon Source at Argonne.

Although petrology has been a mainstay at the lab since it originated, GL research has branched out along the way. Former director Philip H. Abelson broadened the scope 50 years ago to include biology when he extracted amino acids from ancient clamshells. This began a new direction into biogeochemistry that continues today. Current efforts in this field, under the leadership of Marilyn Fogel and Doug Rumble, include stable isotope studies and molecular and biochemical research. This work has been applied to organic geochemistry, paleoecology, oceanography, human nutrition, and ecology.

New equipment and new analytical techniques have yielded unanticipated discoveries. Instruments shared by GL and the Department of Terrestrial Magnetism (DTM) were coupled with a new technique for extracting organic materials from rock. The result is a joint GL/DTM research project characterizing fossil biomolecules in ancient terrestrial rocks. The newly developed methods were then applied to the study of astrochemistry in meteorites. This led to a breakthrough: the identification within meteorites of chemical processes in the early solar nebula that were preserved separately from processes that occurred in the parent body of the meteorite after the planets accreted.

The broadening of geochemistry to include planetary chemistry, biogeochemistry, and astrochemistry has recently spread into astrobiology—the search for the origins of life on Earth and the potential for its existence elsewhere. The Geophysical Lab's strategic approach to astrobiol-



Members of the Geophysical Laboratory, May 1999. First row (from left): Robert Hazen, Marilyn Fogel, Doug Rumble, Neil Irvine, Ho-kwang Mao, Charles Prewitt, Wesley T. Huntress, Hatten Yoder, Joe Boyd, Larry Finger, Yingwei Fei, Bjørn Mysen, George Cody, Ronald Cohen, Russell Hemley, John Frantz. Second row: Pedro Roa, Sue Schmidt, Jinfu Shu, Jack Tossell, Steve Gramsch, Atlaf Carim, Jie Li, Mark Teece, Oguz Gülseren, Richard Ash, Sue Ziegler, Mikhail Eremets, Maceo Bacote, Pablo Esparza, Paul Meeder, Jack Almquist, Roy Scalco, Lawrence Patrick. Third row: Bert Collins, Merri Wolf, Wenjie Jiao, Sébastien Merkel, Zhenxian Liu, Gotthard Sághi-Szabó, Chris Hadidiacos, Tim Filley, Joakim Bebié, Jürgen Konzett, Bill Minarik, Maddury Somayazulu, Viktor Struzhkin. Fourth row: Yanzhang Ma, Bobbie Brown, Margie Imlay, Eugene Gregoryanz, Fred Marton, Alex Goncharov, David George, Shaun Hardy, Huaxiang Fu, Steve Coley, John Straub



Hatten Yoder (left) and Bob Hazen are two members of the astrobiology team at GL.

ogy is twofold: first, to establish the chemistry involved in the emergence of biochemistry under extreme conditions such as are found at high-pressure hydrothermal vents at the ocean bottom; and second, to explore how minerals of the early Earth may have acted as catalysts for the production of biologically important molecules. The goal is to establish a seamless connection between the young geochemical world and the subsequent biochemical world. Another product of this work will be to understand biomarkers—the molecular and isotopic signatures that indicate the presence of life.

The lab began investigations into astrobiology in 1996. Organic geochemist George Cody, mineral physicist Bob Hazen, and experimental petrologist and former GL director Hatten Yoder conducted the first experiments studying the possible role of deep-ocean hydrothermal systems in prebiotic organic synthesis. Their efforts led to the selection of a joint GL/DTM team to be part of NASA's virtual Astrobiology Institute in 1998. The institute's members across the country are connected through the Internet.

Currently, GL's principal focus in this new science is to understand how, under extreme pressure, the hot crustal minerals and gases ejected from the vents into the seawater can result in the chemical resources necessary to support a diverse local biological community. Many types of microbes are found in the hot waters of ocean-ridge vents. They live without light or oxygen on various chemical nutrients and may be representative of the earliest organisms of a young oxygen-free Earth. By understanding these organisms, the GL team hopes to discover the earliest chemical mechanisms used in biology and to develop laboratory methods to understand the evolution from prebiotic chemistry to primitive life.

A closely related avenue for investigation is to understand how to recognize the chemical signs of life on other planets. This knowledge is critical for NASA planetary missions. GL astrochemists and astrobiologists are working to participate in these missions several ways: by working in the laboratory to find ways to spot ancient life from planetary samples; by providing the expertise, and possibly the instrumentation, for selecting samples to return to Earth; and, by using the lab's considerable state-of-the-art instrumentation to analyze the returned materials.

Over the years, the character of science at the Geophysical Lab has changed. Traditionally, it was a small community of scientists with focused objectives who worked in isolation. It has evolved to an interactive group working across scientific boundaries and with many outside collaborators. The lines of inquiry have gone beyond petrology and geochemistry. There is fertile ground in the seams between the traditional disciplines where the new discoveries are taking place. Carnegie has a long history of finding new, emerging scientific fields. It is this tradition that will create a vital and exciting scientific future for the Geophysical Laboratory. Independence as a privately endowed research institution, and the freedom to pursue risky but potentially high-payoff new ventures in science, are the enduring characteristics that will propel the lab into an exciting, productive, and respected future in science.

—Wesley T. Huntress, Jr.

Constance Bertka

An understanding of the formation and evolution of the Earth is linked to understanding the forma-

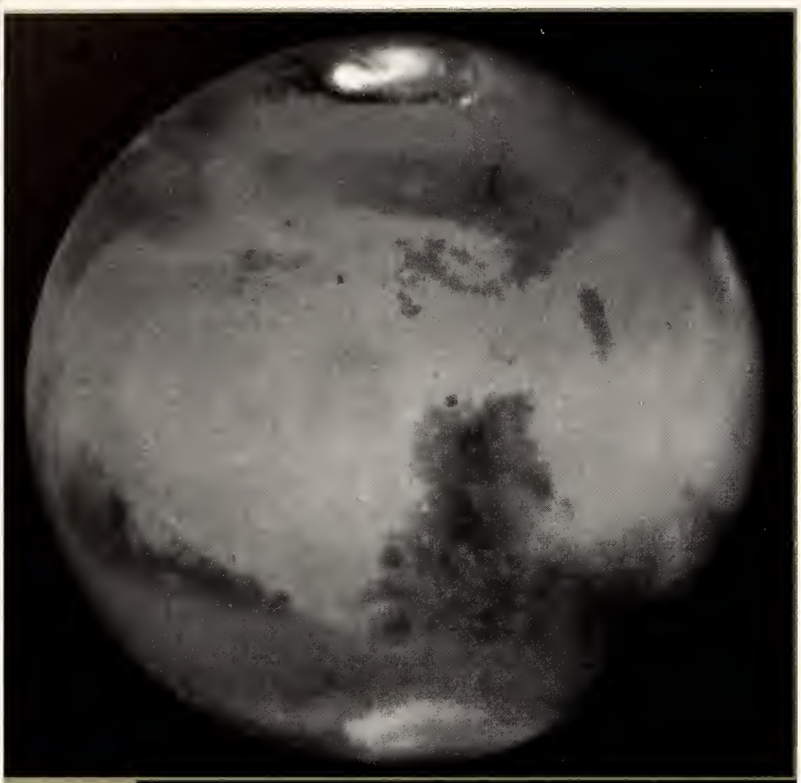


Fig. 2. The planet Mars and the meteorites believed to originate from it, are subjects of research for Connie Bertka.

tion and evolution of its terrestrial neighbors. The focus of Bertka's research is the interior of Mars. She uses high-pressure experimental techniques available with the piston-cylinder and multianvil apparatus. The goal of her work is to provide the necessary data to understand the structure and evolution of the Martian interior, in addition to the formation of the terrestrial planets.

Until recently, only limited geophysical data were available to determine the composition or structure of the Martian interior. Models for the composition were derived from the Martian meteorites. Bertka, with Staff Member Yingwei Fei, determined the high-pressure mineralogy of one meteorite-based model and used this information to model the structure of the Martian interior. The scientists then compared their data with data on the mass distribution of the planet's interior obtained from the Mars *Pathfinder* mission. They determined that a commonly assumed notion that the terrestrial planets have refractory element bulk compositions equivalent to a primitive C1 meteorite is invalid. However, their work did verify another assumption about the mantle of Mars: it is richer in iron than Earth's mantle.

Bertka's research efforts are currently focused on the composition and state of the Martian core. She conducts melting experiments and density determinations of model core compositions. This work will enhance accretion models for the formation of Mars and the other terrestrial planets, and provide the experimental data to compare with seismic data from future Mars missions.

Using existing data from the Martian meteorites and data obtained by the Mars *Pathfinder* mission, Bertka has recently started experiments to understand the formation of textural features in the meteorites and to assess the types of melts that would be produced from partial melting of an iron-rich hydrous source region. Data from current and future Mars missions will also provide information about the geochemistry of surface materials. An experimental database, such as the one Bertka is developing in iron-rich systems, is key to understanding the origin and evolution of these materials.

In addition to her research efforts, Bertka is the director of the Carnegie Institution of Washington's Summer Intern Program in Geoscience. In the past three years, with support from the National Science Foundation, the Camille and Henry Dreyfuss Foundation, and the Carnegie Institution of Washington, the Geophysical Laboratory and the Department of Terrestrial Magnetism have invited over 40 undergraduate and high school students to participate in research projects. During the 10-week summer program the students are introduced to hands-on scientific research with guidance from Staff Members. They also tour other research facilities in the area, participate in a weekly informal lunch meeting with the Carnegie scientific staff, and present their work at a final summer intern symposium. Several of the students have also presented the results of their Carnegie research at national meetings.

Nabil Z. Boctor

Boctor's research focuses on the oldest known Martian meteorite, Allan Hills (ALH) 84001. The 4.5-billion-year-old meteorite contains a complex mineral assemblage that some believe is evidence of

possible relic life on Mars. For life to evolve in any geologic environment, water must be present. The early Martian atmosphere was apparently very different from the present-day one and may have allowed liquid water to exist on the surface of the planet. A way to trace the history of water on Mars is through the isotopic composition of hydrogen. The hydrogen isotope composition of the present-day Martian atmosphere is enriched in the heavy isotope deuterium by a factor of 5.2 (δD = 4200 per thousand (‰) relative to mean terrestrial ocean water). This value is considerably higher than the values observed in any terrestrial environment (δD = -300 ‰ to +100 ‰). The deuterium enrichment in the Martian atmosphere is attributed to isotopic mass fractionation associated with the loss of hydrogen to space through time. Measuring the hydrogen isotope composition of Martian meteorites of different ages, therefore, could provide information on the history of water loss on Mars.

Boctor and coinvestigators Jianhua Wang, Conel Alexander, and Erik Hauri at the Department of Terrestrial Magnetism used the ion microprobe to determine the hydrogen isotope composition of the mineral phases in ALH 84001. The investigation showed three water-bearing phases: phosphate (δD = +166 to +733 ‰), carbonate (δD = +165 to +1165 ‰), and feldspathic glass (δD = +1073 to +1748 ‰). The isotopic compositions of the three phases showed that the water is extraterrestrial, confirming the presence of indigenous water in the oldest known Martian meteorite.

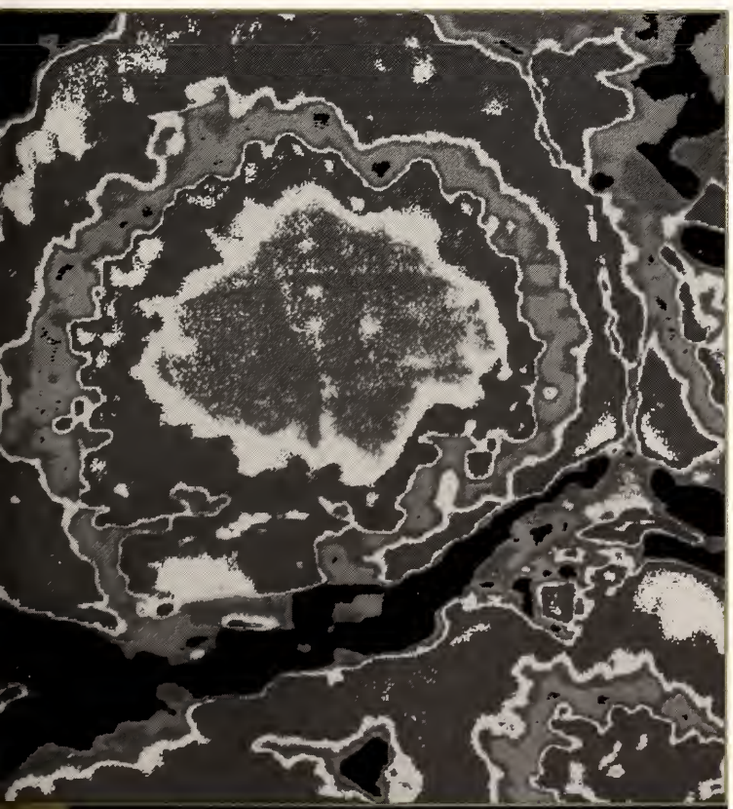


Fig. 3. This is a zoned carbonate globule from Martian meteorite ALH 84001. Magnesium-rich layers (dark gray) alternate with magnesium-poor, iron-rich layers (white to light gray).

The conventional explanation for the high δD values observed in the carbonates and glass is their interaction with hydrothermal fluids that equilibrated with the Martian atmosphere. However, the researchers found the highest δD values were in the glass that formed by impact melting at a pressure of about 4×10^5 atmospheres. This result raised the possibility that the deuterium enrichment in the glass is due to devolatilization and to preferential loss of hydrogen during impact. The scientists measured the δD in impact-melted feldspathic glass (δD = +1612 to +2757 ‰) and mafic glass (δD = +2023 to +2901 ‰) from another Martian meteorite, EETA 79001. This meteorite was shocked at pressures of 6×10^5 to 8×10^5 atmospheres, which was higher than the pressure that ALH 84001 experienced. The results showed a positive correlation between δD values and the shock pressure.

Any fractionation process associated with water loss by devolatilization will produce an inverse correlation between water content and deuterium enrichment. The researchers observed this kind of correlation in ALH 84001. The estimates of the initial water content of the glasses from ALH 84001 needed to produce the range of δD values (+970 to +1650 ‰) are not unusual for feldspathic melts under pressure. These calculations suggest that hydrogen loss by impact may have contributed significantly to the high deuterium enrichments in the impact glasses in both meteorites studied. These results imply that when using hydrogen isotope data from shocked meteorites to infer the history of water on Mars caution should be exercised.

Francis (Joe) Boyd

Joe Boyd joined the Geophysical Laboratory staff in 1955 to conduct high-pressure experiments. One of his many contributions since then includes

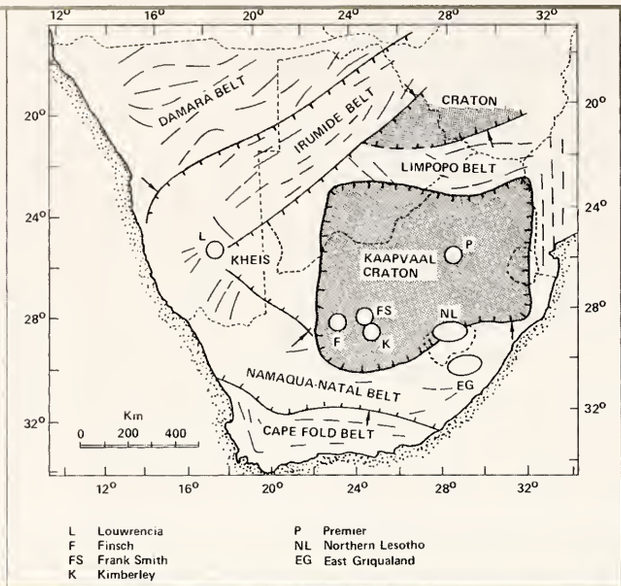


Fig. 4. This map of southern Africa shows the Kaapvaal craton with important kimberlites and kimberlite clusters.

the development of a high-pressure apparatus called the Boyd-England device. This instrument has allowed scientists worldwide to determine critical pyroxene-garnet phase relations—essential data for estimating the depth at which mantle rocks originate. More recently, with fellow Staff Member Yingwei Fei, Boyd created the cubic-anvil apparatus. With a pressure range from 5 to 25 GPa, this equipment allows scientists to conduct phase studies with large-volume samples.

Although Boyd officially retired in 1996, he continues to be an active researcher at the lab. He is well known for his other petrologic work on the nature and structural history of the crust and mantle. He is one of the world's leading experts on the mantle root of the Kaapvaal craton in southern Africa.

Cratons are the kernels on which continents grow. They are much older and deeper than the neighboring crust and mantle. The Kaapvaal craton is some 3.5 billion years old. At 200 kilometers deep, it is well below the crust-mantle boundary. To study it, Boyd gathers and analyzes fragments of mantle wall rocks contained in diamond-bearing volcanic breccias called kimberlite that erupted onto the southern African surface millions of years ago. (The "pipes" through which the kimberlite erupted are now actively mined for diamonds.) Each fragment of mantle rock contains a chemical signature that tells its depth, age, and chemical history. By piecing together the fragments from different locations, Boyd and his colleagues are learning about the Kaapvaal craton's early formation. This information can be applied to cratons in other parts of the world. Boyd is collaborating with Russian scientists, for example, to determine the similarities and differences between the crust and mantle forming the Kaapvaal craton with that forming the Siberian Platform. One of the long-term goals of these studies is to learn how the Earth's first early crust formed—a crust that presumably preceded even that of the Kaapvaal and other ancient cratons around the world.

George Cody

The blend of organic chemistry and geology can address a broad range of scientific questions—from understanding the processes of oil and gas generation to solving the mystery of the origin of biochemistry as it emerged from the molecular chaos of the primitive Earth. George Cody is an organic



Fig. 5. The molecular tapestry of 40-million-year-old wood is shown in this high-resolution x-ray image acquired with the scanning transmission microscope at the National Synchrotron Light Source. The spatial resolution of the image is 50 nm and sample thickness is 150 nm. Contrast is based on the distribution of a specific type of carbon, and this provides a high-resolution chemical "map" of carbon chemistry.

geochemist whose research focuses on devising a unified understanding of the controls on organic reactions within the solid Earth. He explores the roles that temperature, pressure, time, fluid composition, and mineral catalysis play in controlling organic reactions over time. Understanding these processes is a prerequisite to investigating larger issues that tie together the biological, physical, organic, and inorganic world of our planet.

The mechanisms that govern natural organic synthesis and reactions are not restricted to Earth, however. The presence of significant quantities of organic molecules found in certain types of meteorites indicates that the range of viable environments for organic synthesis is extremely broad. In collaboration with others at Carnegie, Cody is working on questions pertaining to the extent of organic synthesis within the presolar nebula and the synthesis and reaction during the subsequent planetary accretion. His specific focus is to characterize the extraterrestrial organic matter within carbonaceous chondritic meteorites. If organic synthesis and reaction are necessary for the emergence of life, then the range and limits of organic stability and reaction need to be defined to set criteria for determining the probability of life on other planets and beyond our solar system. To study organic chemistry in this context, Cody has joined with others at Carnegie to form one of the first groups in NASA's Astrobiology Institute.

A wide range of analytical methods is required to study organic molecules in complex systems. Over the past several years Cody has worked on a particularly promising device that uses a one-of-a-kind soft x-ray transmission microscope based on a synchrotron source. He has been using this instrument to characterize the chemistry of cell wall membranes in plants and to follow the evolution of the chemical differentiation over geologic time as these materials transform into fossil fuels.

Cody also led the effort at the Geophysical Laboratory to obtain a solid-state nuclear magnetic resonance (NMR) spectrometer—an instrument used by scientists at both the Geophysical Lab and the Department of Terrestrial Magnetism at the Broad Branch Road campus. Solid-state NMR has recently evolved into one of the most versatile and powerful tools in solid-phase chemistry. The new equipment is used to address fundamental questions in organic geochemistry as well as questions in many other ongoing research areas.

Ronald Cohen

The Geophysical Laboratory has a long and distinguished history of determining the stability and physical properties of materials experimentally. This work continues today. The materials investigated include Earth's minerals, materials that form the other planets, those used in high technology, and those that are interesting because of the problems they pose to physics and chemistry. One goal of this research is to understand what the underlying physics is that gives rise to the materials' behavior. Cohen and his research group look at the problem by starting with electrons and nuclei; they try to predict and understand mineral and material behavior using fundamental physics.

Three major projects are currently under way in Cohen's lab. The first explores the question: How do transition metal compounds behave at high pressures? Whereas electronically simple compounds like MgO and SiO_2 are well understood and their properties can be predicted quite accurately, transition metal oxides such as FeO are at the frontier of solid-state physics and are poorly understood. Experiments have not yet been able to clarify the properties and physical origins of the behavior of FeO. At high pressures and temperatures (approximately 100 GPa and 1000 K), a NiAs-type structure forms. The reanalysis of the experimental data shows that this product is most likely a polytype of NiAs with anti-NiAs structures (with Fe on the Ni or As sites respectively).[1] Interestingly, the researchers predict the NiAs part to be metallic, and the anti-NiAs part to be insulating. Since this phase may form in the deep Earth near the core-mantle boundary, this behavior could be very important in helping control the variations in the Earth's magnetic field.

1 Mazin, I. I, Y. Fei, R. Downs, and R. E. Cohen, Possible polytropism in FeO at high pressures, *Am. Mineral. 83*, 451-457, 1998.

Currently, Steve Gramsch, a CHiPR fellow, is trying to understand possible high-spin low-spin and metal insulator transitions in the rock salt (NaCl) structure of FeO. He is applying a newly developed method, which includes local electronic correlations, and finds that with increasing pressure a metal insulator transition occurs before a high-spin low-spin transition. This previously had been found theoretically with more conventional methods.[2]

In the second area of research, Cohen is working on materials used in high technology. In particular, he is trying to understand piezoelectricity in ferroelectric perovskites. These materials are used in sonar and medical imaging as well as in dielectrics and nonvolatile computer memories. Postdoctoral associates Henry Fu and Sergei Stolbov are working with Cohen to understand the large strains found in a new class of single-crystal piezoelectrics that will revolutionize the above applications.

Finally, active research is also under way in Cohen's lab to understand the thermoelastic, melting, and rheological behavior of minerals, metals, and compressed gases at high pressures and temperatures.



Fig. 6. Conductivity of water is measured here in a diamond-anvil cell under pressure of 139 GPa.

Mikhail Eremets

In 1999, Eremets joined the Geophysical Laboratory as a Senior Research Scientist. He is currently developing a technique for obtaining electrical measurements at ultrahigh pressures. His goal is to study metallization and to find superconductivity in elemental and simple molecular substances at ultrahigh pressures. His recent work includes the metallization of xenon and search for conductivity of water, nitrogen, and hydrogen at pressures above 2 Mbars.

Mikhail Eremets began his scientific career at the Institute of High Pressure Physics in Troitsk, Moscow, as a Ph.D. student. Eventually, he became director of the high-pressure division. He has more than 20 years of experience in experimental studies of semiconductors and superconductors using various optical techniques in a wide spectral range—from the submillimeter to the ultraviolet. Eremets is also interested in developing high-pressure techniques and has numerous articles and patents on various instruments including the diamond-anvil cell, the Bridgman-type cell, and the piston-cylinder hydrostatic cell.

In the past decade, Eremets has conducted experiments in laboratories in the United Kingdom, France, the Netherlands, Germany, and Poland. He has studied semiconductors and other materials at high pressures in combination with high magnetic fields and low temperatures.

Eremets is particularly interested in diamond and closely related boron nitride (BN). He studied optical properties of cubic BN in the Laboratory for Solid State at the University of Paris-6. Working as a fellow at the National Institute for Research of Inorganic Materials (NIRIM) in Tsukuba, he performed experiments on the laser heating of cubic BN. These experiments yielded numerous results on a mechanism of first-order phase transformation and a phase diagram of BN. During these studies, he discovered boron nitride nanotubes, which are similar to the known carbon nanotube, but have different physical properties.

2 Cohen, R. E., I. I. Mazin, and D. G. Isaak, Magnetic collapse in transition metal oxides at high pressures: implications for the Earth, *Science 275*, 654-657, 1997.

Cohen R. E., Y. Fei, R. Downs, I .I. Mazin, and D. G. Downs, Magnetic collapse and the behavior of transition metal oxides: FeO at high pressures, in *High-Pressure Materials Research, Matenals Research Society Proceedings, Vol. 499*, R. Wentzcovitch, R. J. Hemley, W. J. Nellis, and P. Yu, eds., 1998.

In the last few years, Eremets has turned his attention to the study of the electrical properties of substances at very high pressures. This is an essential, intrinsic area for high-pressure physics because under compression all substances ultimately become metals. However, electrical measurements in a diamond-anvil cell are challenging. Few experiments have been carried out and in those that have, the pressure was limited to 1 Mbar. Eremets, though, resolved numerous experimental difficulties in the preparation of an insulating gasket and electrodes. In collaboration with Japanese colleagues, he carried out studies on optical and electrical properties of sulfur at pressures up to 1.5 Mbar, during which for the first time sulfur was metallized and superconductivity was found in it. This work was done at Osaka University in Japan, where Eremets worked as a visiting professor between 1995 and 1998. During that time, he further developed electrical measurements and pushed the pressure limit up to 2.2 million atmospheres. He succeeded in the metallization of CsI and found superconductivity in it. This high-pressure experiment was performed in combination with millikelvin temperatures and high magnetic fields. With the Japanese scientists, he also transformed oxygen to metals with superconductive properties.

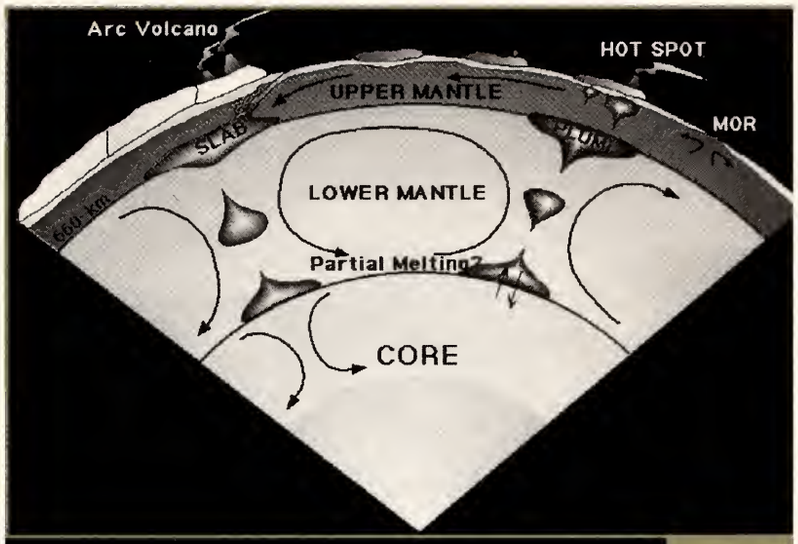


Fig. 7. This diagram shows the relation between mantle plumes and convection in the Earth's interior.

Yingwei Fei

A major goal of petrological, geochemical and geophysical research is to completely describe the Earth's interior—from the crust to the core—to understand the physical and chemical conditions of the planet over time. Recent advances in high-pressure techniques allow scientists to explore the deep interiors of the Earth and other planets via simulations. Yingwei Fei is an expert in using high-pressure devices such as the piston-cylinder, the multianvil apparatus, and the diamond-anvil cell to simulate the high pressure and temperature conditions of planetary interiors. The multianvil apparatus allows scientists to simulate conditions ranging from 5 to 27 GPa. (The larger number is equivalent to a depth of 750 kilometers in the Earth, which is the uppermost part of the lower mantle.) While the diamond-anvil cell allows scientists to reproduce conditions as deep as the inner core, the multianvil apparatus is ideal for scientific investigations that require the analysis of relatively large samples to provide accurate phase equilibrium data.

One particularly vexing problem for earth scientists is the makeup of the Earth's core. Iron certainly is a major part; but what other elements are there? It has been proposed that sulfur (S), carbon (C), and oxygen (O) are the lighter alloying elements that reside there. Fei and postdoctoral fellow Jie Li are conducting experiments to investigate the nature of the core's lighter elements. Their experiments with the multianvil apparatus and the diamond-anvil cell have produced phase transformation and melting relations in the Fe-O-S-C system. This is an important step in understanding how these elements interact at high pressures and temperatures.

Fei and colleagues are also investigating the role of water and potassium in Earth's deep geological processes and the fate of subducted basaltic crust in the lower mantle. A subducted slab of oceanic crust contains significant amounts of water and potassium. What happens to the hydrous and potassium-bearing minerals at such depths? Many believe that hydrous phase transformations in subducted slabs play a large role in mantle processes, including magma generation, water recycling, and possibly the occurrence of deep-focus earthquakes. With the goal of elaborating these phase changes,

Fei focuses on determining the stability fields of several dense hydrous magnesium silicates in the lower mantle. Fei and postdoctoral fellow Jürgen Konzett conducted a series of high-pressure experiments to address transport and storage of potassium in the Earth's upper mantle and transition zone. Postdoctoral fellow Wenjie Jiao and Fei, in collaboration with Department of Terrestrial Magnetism Staff Member Paul Silver, are developing a new multichannel acoustic emission data collecting system to detect acoustic emissions at high pressures and temperatures. This new system will allow them to test proposed physical mechanisms of deep earthquakes.

Much of what scientists learn about our Earth can be applied to other planets. Fei is collaborating with Research Scientist Connie Bertka in investigating the internal structure of the planet Mars. Since there is no seismic data for Mars, scientists must rely on models and high-pressure and temperature experiments. Fei and Bertka are developing a model of the Martian interior that starts with a chemical composition derived from Martian meteorites. On the basis of recent geophysical data from Mars *Pathfinder*, the two researchers found that C1 chondrite accretion models are not sufficient to explain the formation of Mars and the other terrestrial planets.

Marilyn Fogel

A vast reservoir of carbon lies beneath the Earth's surface. It is composed of organic material millions of years old that has a mass many times larger than that of all living animals and plants combined. It is critical to us because it is the source of all of our fossil fuels—oil, gas, and coal. Carbon is also critical because within it, and in the organic molecules that give rise to it, are the keys to understanding the biological and geological evolution of our planet. Understanding the coevolution of biology and geology is essential for management of our resources and predictions of climate change in the next century.

Fogel's aim is to unlock the secrets within the Earth's carbon record through a unique combination of methodologies and techniques. She applies advanced biochemical, isotopic, and spectroscopic techniques—some borrowed from the medical community—to learn how and why biochemicals survive and transform into other molecules on the Earth's surface to eventually become part of the carbon reservoir below. She is interested to learn, for example, how carbohydrates make up such a large fraction of the organic matter in geological samples, when for years it was believed that carbohydrates were destroyed early in the decay process. She wonders how nonbiological complexes of carbohydrates with proteins and nucleic acids become structurally complex and stable geopolymers that withstand the test of time. To investigate such puzzles, her work straddles the territory between geochemistry and molecular biology.



Fig. 8. Fogel and colleague Gifford Miller discuss their ideas and data in their field camp on the shores of Lake Gregory, located within an Aboriginal reserve in the Great Sandy Desert of Western Australia.

Fogel is also interested in studying past global change by reconstructing ancient environments using tools of isotopic analysis. Her rationale begins with the dictum "You are what you eat." An organism's tissues retain the nitrogen, carbon, and oxygen isotopic signatures of its diet and environment. These signatures are retained over millions of years in fossils, particularly in shell or tooth fragments, and can be measured in the laboratory. Fogel has analyzed ancient emu eggshell, for instance, to learn how the practice of large-scale burning by ancient humans in the Australian Outback has altered the climate on a

continental scale. Learning how such ancient environments have been changed by humans can help scientists better understand how humans now and in the future alter the global landscape.

Fogel is currently working in a new direction with fellow Staff Members George Cody, Douglas Rumble, and Bob Hazen. They and others at the Geophysical Laboratory are members of NASA's Astrobiology Institute, which is involved in studies searching for evidence of early forms of life on Earth, on other planets, and outside our solar system.

John Frantz

John Frantz is interested in the investigation of the chemical structure of amorphous materials, such as silicate melts and aqueous fluids, as they pertain to processes involving heat and mass transfer in the terrestrial planets. As the Earth and neighboring terrestrial planets continue to cool, materials are constantly recycled throughout the crust and mantle, resulting in chemically diverse rock compositions. Since amorphous materials are the primary agents in recycling, it is necessary to understand their chemical structure and associated physical properties to understand the processes controlling planetary evolution. In recent years, Frantz has investigated the chemical structure of both silicate melts and hydrothermal fluids.

Frantz has also developed a furnace assembly, which permits for the first time the routine study of polymerization of silicate tetrahedra to temperatures above 1600°C at atmospheric pressure using Raman spectroscopy. He and Bjørn Mysen have successfully used this technique to investigate the structure of silicate melts involving alkalis, alkaline earths, and aluminum.

More recently Frantz's interests have focused on the structure of hydrothermal fluids. His experiments currently involve supercritical fluids using Raman spectroscopy in conjunction with hydrothermal optical pressure vessels. He designed and built an optical cell fitted with diamond windows suitable for in situ measurement of the Raman spectra of fluids to 600°C and 4000 bar for this work.

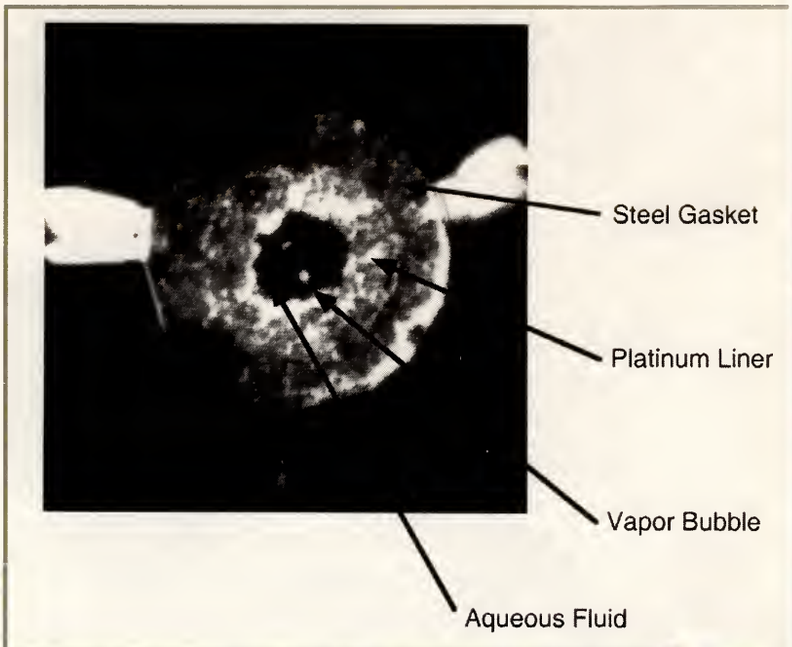


Fig. 9. This is a view of aqueous magnesium sulfate solution shown through a microscope in the heated diamond cell.

Frantz is also investigating supercritical fluids containing both water and carbon dioxide—a vital study since carbon dioxide is a major component of natural hydrothermal fluids. As part of this project, he successfully developed a methodology by which he can directly study CO_2-H_2O binary fluids in situ using Raman spectroscopy. He is also studying the stability and complexing of salts of aliphatic acids in hydrothermal fluids; salts might be important agents for mass transport since they may exist metastably for significant periods of time.

Over the next two or three years, Frantz hopes to conclude these studies and change his research to in situ monitoring and theoretical modeling of natural hydrothermal fluids at oceanic ridges. As a first step in this new direction, he is developing an instrument to measure the hydrogen fugacity of the high-temperature fluids in these environments.

Alexander Goncharov

Alexander Goncharov has been working with Staff Members Ho-kwang Mao and Russell Hemley for almost six years to develop methods in optical spectroscopy for ultrahigh-pressure research. Optical spectroscopy is one of the most informative techniques for ultrahigh-pressure studies. Its

importance arises from the power it has to study a wide variety of phenomena, and the transparency of the high-pressure cell's diamond windows over a wide spectral range. Optical methods are unsurpassed in many cases, such as studying low-Z containing materials, disordered materials, phase transitions, pressure calibration, and lattice dynamics.

Goncharov has built a variety of new optical instruments including GL's infrared (IR) facility at the U2 beamline of the National Synchrotron Light Source (NSLS), Brookhaven National Lab; GL's low temperature-ultrahigh pressure system for Raman and infrared experiments; and Raman/fluorescence spectrometers at the X17C beamline of the NSLS and Sector 13 of the Advanced Photon Source. These contributions have made it possible to routinely perform numerous optical experiments at ultrahigh pressures.

Goncharov, in collaboration with Staff Members at GL, conducted experiments to examine the behavior of simple molecular substances at megabar pressures. Among the most exciting results was the discovery of a new class of excitations in orientationally ordered low-temperature phases of solid hydrogen and deuterium. Another breakthrough was the first unambiguous experimental evidence of the existence of nonmolecular high-pressure modification of ice with symmetric hydrogen bonds.

Recently, Goncharov was involved with the upgrade of the U2 beamline. This substantially improved the performance in the far-infrared spectral range and has made it possible to measure far-infrared spectra in the megabar pressure range. Goncharov is also working on a new design for a laser spectrometer with holographic optics.

Robert Hazen

Robert Hazen worked with former Staff Member Larry Finger for two decades to establish the field of high-pressure crystallography—the study of crystal structures at high pressure. Their work has led to a deeper understanding of compression mechanisms in solids, as well as identification of numerous high-pressure phase transitions in minerals and related compounds. They have also predicted a variety of new structures, including mineral-like compounds that may have applications as ceramics, abrasives, and materials for trapping and isolating the radioactive atoms found in nuclear waste. When they began, their high-pressure work was groundbreaking. Today, researchers around the world use their techniques.

Hazen has turned his attention to a new area—the study of high-pressure organic synthesis deep within the Earth. Carbon, the central element of life, exists in high-pressure and high-temperature environments. Hazen, in collaboration with other Staff Members at the lab—George Cody, Marilyn Fogel, Hatten Yoder, and Russell Hemley—is conducting experiments to examine the pathways by which the simplest organic compounds, like carbon, may have combined deep in the Earth's ancient crust to form the molecules essential to life. Among the most exciting potential outcomes of these studies would be the discovery of the evolutionary sequence of chemical reactions leading to the origin of life.

The organic synthesis work is complemented by studies of carbon and nitrogen isotopes preserved in fossils. Hazen, working with the Department of Terrestrial Magnetism's ion microprobe facility and with paleontologists at the Royal Ontario Museum in Toronto and at Harvard University, is examining extraordinary specimens in which original atoms of ancient life are preserved. These studies hold the promise of understanding biochemical

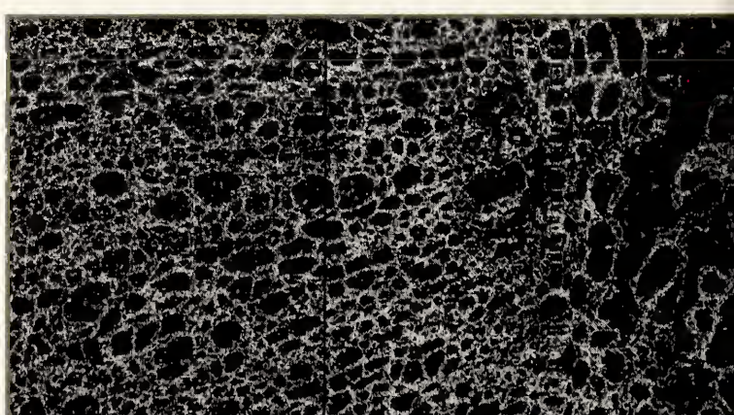


Fig. 10. Microprobe maps of fossils reveal compositional details that may provide clues about the biochemistry of extinct animals and plants. This cross section of a 50-million-year-old dicotyledon twig from Canada reveals cellular details in ancient carbon.

aspects of organisms that became extinct hundreds of millions of years ago.

During the last several years, Hazen has also been an advocate for the reform of science education, at both the K-12 and the undergraduate level. He helped write the National Science Education Standards introduced by President Clinton in 1995, and has served on the Executive Board of the National Research Council's National Committee for Science Education and on advisory boards for NOVA, *Encyclopedia Americana*, and the National Science Resources Center. In 1997, he coauthored a book with Carnegie's president, Maxine Singer, titled *Why Aren't Black Holes Black?: The Unanswered Questions at the Frontiers of Science*. Intended to inform and intrigue science enthusiasts beyond the academic sphere, this work examines 14 of the most compelling mysteries facing scientists today. It is the latest of a long list of books about science that Hazen has written.

Russell J. Hemley

Rus Hemley continues to explore the remarkable behavior of materials when they are subjected to extreme pressures, up to and beyond 300 GPa (3 Mbar), at temperatures ranging from millikelvins to above 5000 K. It is becoming increasingly clear that such studies have implications that span the physical sciences, from fundamental chemistry and physics, earth and planetary science, to materials science and high technology. Research within Hemely's group during the past year has continued to uncover new phenomena in molecular materials at very high pressures. For instance, the researchers pinpointed the transition pressure of H_2O-ice from its normal molecular form to its high-density nonmolecular state. They also found unusual quantum mechanical phenomena associated with this transition. These experiments, combined with related studies of hydrogen and methane, reveal the nature of materials that comprise the large planets of the solar system. Some of the group's other high-pressure studies of molecular systems include the study of superconductivity in organic conductors, and in situ monitoring of the organic reactions under hydrothermal conditions.

Hemley's group is also focusing on the oxides, silicates, and metals that form major constituents of our planet. Long thought to be a solved problem, the high-pressure behavior of silica continues to produce new surprises. Important advances have been made in both theory and experiment, including the evidence for new forms of silica that may exist deep within the mantle. Recent experimental data were used to develop a theory for silica's major high-pressure transition at 50 GPa; this provides a basis for evaluating the geophysical signature of free silica in the lower mantle. The pressure dependence of the stability of quartz—the common form of silica found in the Earth's crust—was tracked using light-scattering techniques. The experiment revealed the origin of the pressure-induced transformation of the material to a dense glass. The group had discovered this phenomenon in the 1980s. New x-ray diffraction and spectroscopic studies have uncovered novel phenomena in iron-bearing oxides and silicates, including electronic spin transitions and magnetic collapse. These latter studies also include the first direct measurements of the elasticity, texture, and flow properties of iron—crucial information for understanding seismological observations of the Earth's core.

Most of the discoveries mentioned above were made possible by the group's ability to continually develop new techniques in high-pressure experimentation. Among the most important have been those involving high-intensity synchrotron radiation, such as new techniques for x-ray diffraction of materials at pressures and temperatures found at the Earth's core, x-ray fluorescence spectroscopy, and new high-pressure inelastic x-ray scattering. In fact, the group has launched a major program to build a high-pressure synchrotron x-ray facility at the Advanced Photon Source, Argonne National Laboratory to carry out these studies in a dedicated fashion. This new facility offers many opportunities and will complement the dedicated high-pressure synchrotron beamlines the group uses at the National Synchrotron Light Source at Brookhaven Lab, including the just-completed dedicated high-pressure synchrotron infrared beamline. This synchrotron work also complements technical advances in other areas. Some examples are high-pressure magnetic susceptibility and electrical con-

ductivity techniques for investigating new superconductors and novel metals, and the development of new synthetic diamond anvils for compressing larger samples, reaching higher pressures, and performing an even wider range of measurements.

T. Neil Irvine and Hatten S. Yoder, Jr.

Metasomatic rocks are formed when an original rock is transgressed by mineralized solutions (liquid and/or vapor) that react in passing to produce material of new composition. Commonly the new rock replaces the original on an approximately volume-for-volume basis. Metasomatic rocks are widespread in the Earth's crust and upper mantle, and they frequently are exotic in mineralogy and texture. Many feature monomineralic zones; some are economically important as ore deposits; almost all are problematic in origin. The nature and origin of the fluids and the mechanics of the reaction processes are especially difficult to define.

The Skaergaard intrusion is situated in East Greenland, just north of the Arctic Circle. It solidified from a body of magma (molten rock) roughly 10 km long, 7 km wide, and 3.5 km thick. The intrusion is renowned for spectacular primary layering, and it is by virtue of this layering that the secondary metasomatic bodies considered here are recognized (below). These bodies are mostly anorthosite, a white rock composed largely of the mineral plagioclase (a solid solution of $CaAl_2Si_2O_8$ and $NaAlSi_3O_8$), but many have thin basal rims of peridotite, a brown rock rich in olivine (a solid solution of Mg_2SiO_4 and Fe_2SiO_4). The anorthosite bodies typically wend through their layered host rock without appreciably displacing its stratification, this being prime evidence that volume-for-volume replacement, and the bodies are ideal for study because they are well exposed, convenient in size (1-10 m long), and distinctively simple. It is reasonably established that the host rock (called gabbroic troctolite) originated by sedimentation of plagioclase and olivine crystals on the floor of the original magma body as it cooled and solidified, and that the metasomatism was imposed as the pore liquid between the accumulated crystals gradually solidified. Water was evidently important to the metasomatism, because the anorthosite plagioclase contains tiny, H_2O-rich vapor bubbles.

The metasomatism is further explored here through a new experimental observation that addition of H_2O to olivine-plagioclase cotectic melts in a model system Mg_2SiO_4-$CaAl_2Si_2O_8$-SiO_2 strongly shifts their compositions toward plagioclase.

The diagram below illustrates schematically how such shifting might induce mineral exchange reactions in troctolite, and the drawing (right) interprets the Skaergaard metasomatic processes using these reactions. The dry liquid, L^o, is portrayed as original pore liquid being gradually filter pressed upward through the layered crystal pile by com-



Fig. 11. Metasomatic anorthosite formed by replacement of layered gabbroic troctolite in the Skaergaard intrusion is shown here. A thin, dark rim of peridotite follows the lower edge of the anorthosite. The layering was almost horizontal originally, and all the rocks have been tilted to the right.

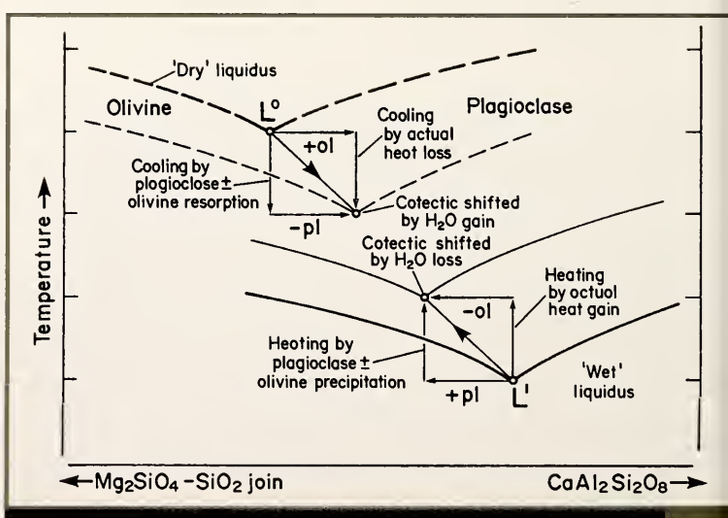


Fig. 12. This image shows possible interactions of olivine-plagioclase cotectic liquids with troctolite (plagioclase-olivine rock) from gains or losses of H_2O and heat, based on newly defined relations for the system Mg_2SiO_4-$CaAl_2Si_2O_8$-SiO_2-H_2O at 5 kilobars pressure.

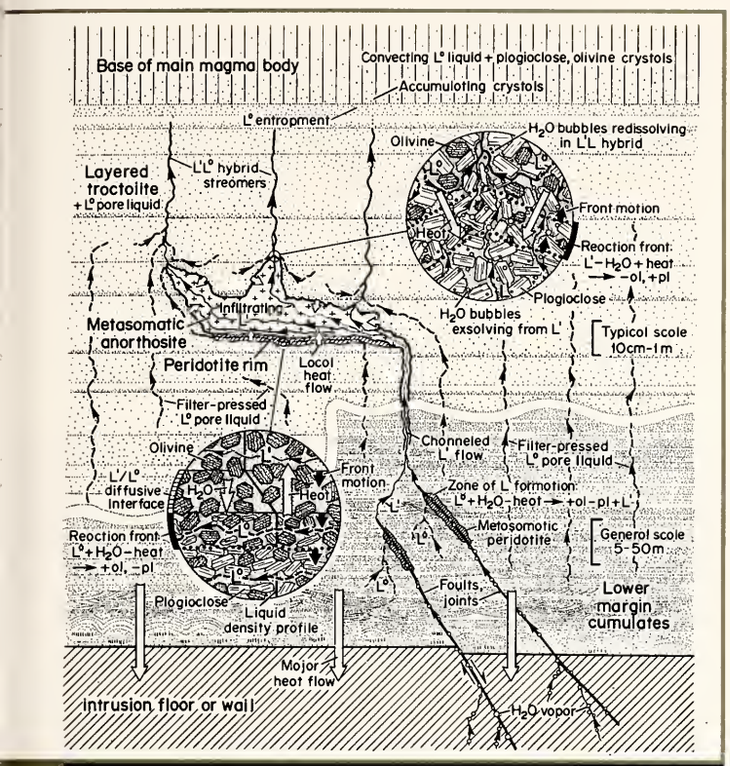


Fig. 13. Physical processes are inferred for the formation of Skaergaard metasomatic anorthosite and peridotite in this diagram.

paction. Hydrous liquid L' forms in the lower part of the intrusion where H_2O entering along fractures from the floor or wall rocks interacts with the first L^o it encounters; then, being the more fluid and buoyant liquid, L' preferentially rises along permeable channels to local sites of metasomatism near the top of the crystal pile. Metasomatic anorthosite forms where L' dehydrates by boiling; the peridotite rim at its base develops concurrently below a density graded L'/L^o diffusive interface.

Ho-kwang (Dave) Mao

Ho-kwang (Dave) Mao joins his principal collaborator and fellow Staff Member, Russell Hemley, in the belief that high-pressure research is reaching a turning point and may soon emerge as a dominant branch of modern science. Mao is a pioneer in ultrahigh-pressure technology. He has repeatedly demonstrated how innovative high-pressure experimentation has exposed new scientific phenomena critical to solving problems in physics and the planetary sciences. As the field grows, he foresees that it will also add new dimensions to research in chemistry, the material sciences, and technology.

Mao is a principal investigator at the Center for High Pressure Research (CHiPR) and director of the newly established high-pressure collaborative access team at the Advanced Photon Source at Argonne National Laboratory. Mao is an expert on research using multimegabar techniques, especially with the diamond-anvil cell. He and former colleague Peter Bell first reached 1 megabar static pressure in 1976, an advancement that doubled the previous pressure limit. Three years later, Mao and Bell became the first to compress hydrogen to solid form at room temperature. Mao and his colleagues have been steadily improving the multimegabar technique ever since, integrating it with methods of analysis such as synchrotron x-ray diffraction and infrared, Raman, and other kinds of spectroscopies. By 1990, the high-pressure researchers reached 1.8 megabars and detected evidence of a transition to metallic hydrogen in the molecular form.

Mao and his collaborators have made a myriad of discoveries about physical and chemical phenomena at high pressures, including pressure-induced amorphization and crystallization and electronic and structural phase transitions, as well as discoveries relevant to planetary interiors. Several years ago, for example, Mao participated in an investigation of the core of Mars. With his colleagues, including Charles Prewitt and Yingwei Fei, he suggested that sulfur might be a possible light-element component of the Martian core. The year before, Mao and Fei raised the possibility that sulfur and oxygen could both be components of the Earth's largely iron core.

Bjørn Mysen

Bjørn Mysen is intrigued with the processes that led to the formation and evolution of the Earth. He is particularly interested in the physical chemistry of melting and crystallization, as well as in materials and energy transfer and transport processes in the interiors of the Earth and terrestrial planets. The interactions between molten silicate (magma), its crystalline equivalent, and water are central to his investigation; they influence the fundamental physical and chemical processes within the Earth.

At high pressure, water is released from silicate melts, altering the surrounding volume of fluid;

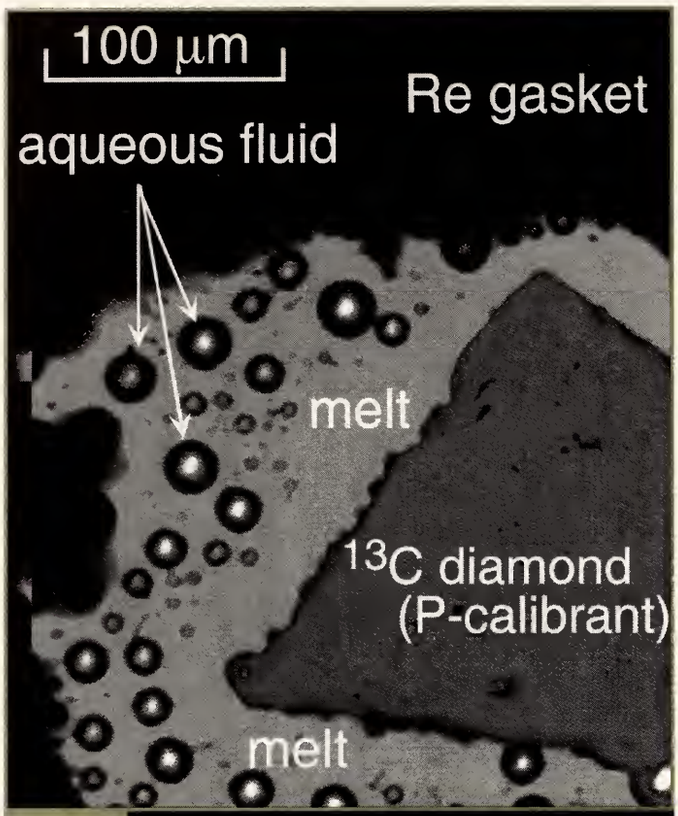


Fig. 14. This is a photomicrograph of coexisting H_2O-saturated silicate melt and silicate-saturated bubbles of aqueous fluids taken in situ in the diamond-anvil high-pressure cell at 0.9 GPa and 910°C.

this may govern the explosive nature of many volcanic processes. These fluids also act as solvents for silicates, and thus function as principal agents to transport materials within the Earth. This transport also results in the enrichment of elements that ultimately provide economically important ore deposits. Much of Mysen's research spotlights a common link between the mixing behavior of solutions in silicate melts and in silicate-bearing aqueous solutions, and the transport properties, or rheology, of fluids and melts.

Materials like these are measured in the lab by examining their structural features microscopically. This requires examining silicate melts and fluids at high pressures and temperatures comparable to those in the Earth's interior. Mysen uses these structural data to model the materials' thermochemical and transport properties. This in turn allows him to develop a framework to predict the melting, aggregation, ascent, and crystallization of the silicates melts and aqueous fluids.

Charles T. Prewitt

Charles Prewitt's research involves the synthesis and characterization of mineral analogs and new materials that are interesting to both geoscientists and materials scientists. Along with Staff Members Larry Finger and Robert Hazen, and Research Scientist Hexiong Yang, Prewitt maintains and operates the Geophysical Laboratory's x-ray diffraction lab and, with the retirement of Finger in July 1999, has taken on an expanded role. Prewitt also uses synchrotron facilities in the U.S. and abroad for his work. He has several current research projects.

Funds from the W. M. Keck Foundation were used to match a National Science Foundation, Division of Earth Sciences grant to purchase a Bruker CCD single-crystal x-ray diffractometer. Larry Finger and Prewitt were the principal investigators. The instrument was delivered in October 1998 and, after learning how to operate the equipment and reduce the data, a number of different scientists have used it for a variety of projects. The researchers are pleased with its capabilities and believe it will have a major impact on productivity, enabling scientists to perform experiments that would be difficult or impossible with the older diffractometers. The early operation of the instrument was aided substantially by a predoctoral fellow, Przemyslaw Dera, who is a graduate student at Adam Mickiewicz University in Poznan, Poland. Dera returned to Poland in March to complete his Ph.D. thesis and will return to Carnegie in January 2000 as a postdoctoral fellow to continue working with the group. Other scientists who have used the equipment include Finger, Prewitt, Hexiong Yang, Jeff Post (Smithsonian Institution), Altaf Carim (Penn State University), and two summer interns, Kenneth Kehoe (University of Wisconsin) and Jason Nicholas (Franklin and Marshall College). Several papers based on data from the diffractometer have been submitted for publication, and several others are in preparation.

Prewitt is also interested in research on hydrous magnesium silicates, particularly in the addition of components other than those found in the MgO-SiO_2-H_2O system. High-pressure hydrous

silicate phases have attracted much attention for the past 30 years because of the implications they have for the presence of water in the Earth's mantle and the effects they have on Earth processes. Previous studies on hydrous silicates were focused primarily on the MSH (MgO-SiO_2-H_2O) system, and a number of phases were identified and labeled as 10Å, 3.65Å, A, B, C, D, E, F, G, and superhydrous B (the "alphabet phases"). Because the mantle contains elements other than those in the MSH system, Jürgen Konzett, Charles Prewitt, and Hexiong Yang investigated more chemically complicated hydrous silicate phases synthesized at high pressures and temperatures using the multianvil apparatus. The synthesis and characterization include the following hydrous phases:

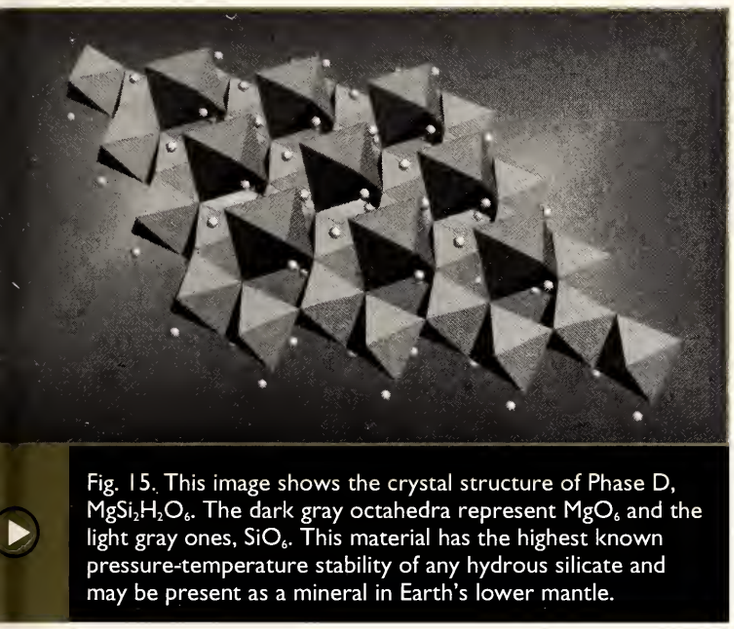


Fig. 15. This image shows the crystal structure of Phase D, $MgSi_2H_2O_6$. The dark gray octahedra represent MgO_6 and the light gray ones, SiO_6. This material has the highest known pressure-temperature stability of any hydrous silicate and may be present as a mineral in Earth's lower mantle.

^{M4}K-substituted K-richterite, $K(KCa)Mg_5Si_8O_{22}(OH)_2$
(15 GPa, 1400°C);

Clinopyribole, $K_{0.96}Ca_{1.56}Na_{2.51}Mg_{6.01}Al_{1.12}Si_{12}O_{34}(OH)_2$
(10 GPa, 1200°C);

Hydrous phase (aenigmatite structure), $Na_2(Mg_{5.30}Al_{0.48})Si_{5.91}O_{18}(OH)_2$
(10 GPa, 1250°C);

Na-phase X, $(Na_{1.16}K_{0.01})(Mg_{1.89}Al_{0.14})Si_2O_7H_{0.65}$
(10 GPa, 1250°C);

K-phase X, $K_{1.54}Mg_{1.93}Si_{1.89}O_7H_{1.04}$
(16 GPa, 1300°C)

Identification and structure refinements of these phases not only provide researchers with insights into crystal chemistry of high-pressure hydrous silicates, they also expand the knowledge of deep Earth mineralogy. The table shows several new phases with structures related to Phase E, one of the major candidates to be actually present in the mantle, but as yet not identified as a mineral. Addition of Fe^{3+} results in structures with different unit cells and symmetries but similar structural components.

Douglas Rumble III

Oxygen isotope geochemistry is the single most powerful research tool available for the study of interactions between water and rocks. Water alters rocks by chemical reactions such as solution, replacement, and precipitation, and at the same time indelibly changes the rocks' oxygen isotope composition. Oxygen has three stable, nonradioactive isotopes—^{16}O, ^{17}O, and ^{18}O. Seawater, rainwater, glacier ice, groundwater, and extraterrestrial water each have distinctive and identifiable ratios of the isotopes. By measuring the oxygen isotope ratios in rocks and minerals, the sources and amounts of ancient waters long drained away can be estimated.

Projects under way in Doug Rumble's laboratory accurately illustrate the wide applicability and power of oxygen isotope geochemistry. Rumble is analyzing oxygen isotopes in high-pressure minerals from a continental collision zone in northern Kazakhstan. The samples are unique to the planet because they contain diamonds in a matrix of metamorphosed sediments rather than the more typical occurrence in volcanic rocks. Together with

Phase	S.G.	Composition	Synthesis
E	$R\bar{3}m$	$Mg_{2.40}Si_{1.21}O_6H_{2.36}$	16 GPa, 1000°C
Brown	$P6_3/mmc$	$Mg_{2.29}Fe^{3+}_{0.60}Si_{1.01}O_6H_{2.15}$	14 GPa, 1400°C
Green	$P6_122$, $P6_522$	$Mg_{2.13}Fe^{3+}_{0.59}Si_{0.87}O_6H_{2.52}$	14 GPa, 1400°C
Dark green	$R32$, $R3m$, $R\bar{3}m$	$Mg_{1.96}Fe^{3+}_{0.87}Si_{0.63}O_6H_{3.05}$	14 GPa, 1400°C

geologists from the Tokyo Institute of Technology (TIT), Waseda University, Yokohama University, the Geological Survey of Japan, and Stanford University, Rumble participated in mapping and sampling diamond-bearing rocks of the Kokchetav massif in August 1999. Graduate students from Waseda and TIT are now analyzing the samples in Rumble's laboratory. The goal of the study is to identify the source of the diamond-containing rocks. The isotopic information will be used to understand how surface rocks can be subducted to depths of 125 kilometers, or more, and return to Earth's surface without losing their definitive surface characteristics. It should be possible to reconstruct ancient environmental conditions recorded by sediments before they were driven into the Earth's mantle by continental collision.

NSF postdoctoral fellow Henry Fricke is using the ultraviolet (UV) laser oxygen isotope microprobe and other analytical techniques to investigate the record of ancient climate stored in dinosaur teeth. These methods work because the oxygen isotope ratio of rainwater is influenced by local climate. Animals drink the rainwater, which in turn influences the oxygen isotopic composition of their growing teeth. A UV laser study of several small dinosaur teeth indicates that they grew rapidly, and may be used to study seasonal changes in temperature during the Cretaceous period. Analyses of dinosaur teeth from different localities in North America using conventional techniques indicate that temperatures were much warmer during this same time period, particularly in the polar regions.

Richard Ash, NASA postdoctoral fellow, is studying meteorites with the UV laser oxygen isotope microprobe. He has found isotopic evidence of the effects of 4.5-billion-year-old ice that accumulated with the metallic and rocky components of meteorites early in the history of the solar system. Continuing accretion from the solar nebula grew planetesimals big enough that the internal radioactive decay melted ice chunks. Liquid water percolated through the metal-rock mixture, altering the isotopic composition as it moved, and leaving behind a record that survived even the fiery flight through Earth's atmosphere.

None of the projects would be possible without the use of state-of-the-art equipment, much of which must be crafted in-house. The infrared laser oxygen isotope probe was invented in this laboratory by postdoctoral fellow Zach Sharp 10 years ago and an updated instrument remains in demand. The new UV laser oxygen isotope microprobe was developed through the efforts of many researchers, including former German Science Foundation postdoctoral fellow Uwe Wiechert, former Carnegie fellows Ed Young and James Farquhar, and Rumble. The UV microprobe is opening up new research opportunities because of its capability for in situ, spatially resolved analyses.

Viktor Struzhkin

Viktor Struzhkin joined the Geophysical Lab's high-pressure group, led by Ho-kwang Mao and Russell Hemley, in October 1994. He started working with diamond-anvil cells on projects exploring superconductivity at extremely high pressures. This work was initiated by Yuri Timofeev, who is still an active collaborator in the effort. The experiments have been very successful—superconductivity measurements were obtained for the first time on niobium at megabar pressures of 140 GPa and on sulfur at 155 GPa. Recent developments in instrumentation have improved the sensitivity of the technique substantially, allowing the measurement of superconductive magnetic signals from samples only 30 microns in diameter and a few microns thick. Recent successful measurements of sulfur to 230 GPa confirmed that this is the technique of choice for multimegabar experiments. This method will allow researchers to explore novel



Fig. 16. From left are Rus Hemley, Dave Mao, and Viktor Struzhkin, members of GL's high-pressure group.

metallic phases of light elements that are fundamentally and astrophysically important, partly because of their potential as high-temperature superconductors. One of these novel phases may be metallic hydrogen, which is widely believed to have a very high critical superconducting temperature. The experimental work recently received an added dimension—new developments in magnetic techniques, by Yuri Timofeev, to be used to study ferromagnetic materials. Senior Research Scientist Mikhail Eremets, who recently arrived at GL, brought another technique for resistivity measurements. This method extends the possibilities for studies of superconductors and magnetic materials even further.

Struzhkin is also involved with other synchrotron-based techniques recently developed at the Geophysical Laboratory, including those that probe the magnetic and electronic structure of metals and magnetic materials. These techniques were developed in collaboration with the National Synchrotron Light Source at Brookhaven and the Advanced Photon Source at Argonne National Laboratory. Recently, Struzhkin investigated the local magnetic structure of FeS and FeO with x-ray emission spectroscopy. The high-pressure group's recent breakthroughs in the creation and characterization of novel metals and superconductors are providing extraordinary opportunities that Struzhkin and colleagues plan to pursue in their upcoming research.

In addition to his other work, Struzhkin devotes a considerable portion of his research time investigating simple molecular solids using spectroscopic techniques. He is a member of the team that discovered the symmetric form of ice. Synchrotron infrared spectroscopy was the main tool used to investigate the transition region in detail, and Struzhkin was responsible for the analysis of the data that revealed the underlying pressure-induced changes in ice.

David Virgo

Throughout his career, David Virgo's major field of concentration has been the use of crystal, chemical, and other structural information to characterize properties and processes in rock-forming minerals and silicate melts. His early work focused on intercrystalline partitioning between coexisting feldspar phases in metamorphic rocks and on intracrystalline equilibria, namely the distribution of iron cations between crystallographically distinct sites in ferromagnesian minerals. These initial interests remain a top priority in his research today. In a series of classic studies, he has shown how Fe-Mg order-disorder equilibria in pyroxenes and amphiboles can be used as a powerful means to determine temperature-time paths of metamorphic and igneous rocks on the Earth and the Moon. This interest has led him to projects using thermodynamic calibrations of heterogeneous phase equilibria between coexisting minerals in xenoliths entrained in basaltic and kimberlitic magmas to clarify the oxidation state of the Earth's upper mantle. An extension of these studies, to include the crystallographic controls of Fe^{3+} and Fe^{2+} in lower mantle phases, aims at modeling the oxidation state of the lower mantle. Both these latter studies provided unique answers to fundamentally important questions concerning the Earth's early evolution.

Virgo also devoted a considerable portion of his research time to experimental studies of the structure of silicate glasses and to the relationships between structure and derivative physical and chemical properties. He was an integral part of the extensive effort at the Geophysical Laboratory on silicate melt structure beginning around 1979, when he demonstrated how Mössbauer and Raman spectroscopic data can be used to determine the cationic and anionic speciation in silicate glasses. In these pioneering studies, he advocated the concept of coexisting structural units in melts, a concept that at the time was not fashionable, but that today is in accord with the extensive body of spectroscopic data of silicate glasses and liquids.

Virgo's current research concerns experimental studies of the iron oxidation mechanism in magmatic hydrous minerals such as micas, amphiboles, and allanites. He believes that these studies will lead to a new magmatic geohygrometer. Thus far his work has led to important predictions regarding the water contents of Martian magmas, which in turn have raised questions concerning the possibility of prior existence of life on Mars.

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Anil K. Singh, *National Aerospace Laboratories, Bangalore, India*
Nicolai V. Sobolev, *Institute of Mineralogy and Petrology, Academy of Sciences, Novosibirsk, Russia*
Gerd Steinle-Neumann, *University of Michigan*
Lars Stixrude, *University of Michigan*
Mikhail Strzhemechny, *Verkin Institute of Low-Temperature Physics and Engineering, Ukrainian Academy of Sciences, Kharkov, Ukraine*
Jack Tossell, *University of Maryland*
Noreen C. Tuross, *Smithsonian Institution*
Qingchen Wang, *Chinese Academy of Sciences*
Wansheng Xiao, *Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou*
Hak Nan Yung, *Chinese Academy of Sciences, Guangzhou*
Ru-Yuan Zhang, *Stanford University*
Yi-Gang Zhang, *Academia Sinica, China*
Guangtian Zou, *Director of Center for Superhard Materials, Jilin University, Changchun, China*

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[1]Retired June 30, 1999
[2]Retired September 30, 1998
[3]From September 28, 1998
[4]Regular staff from July 1, 1998
[5]From April 1, 1999
[6]From January 4, 1999
[7]From August 10, 1998
[8]To February 5, 1999
[9]From August 1, 1998
[10]Joint appointment with DTM
[11]From March 1, 1999; joint appointment with DTM
[12]To December 3, 1998
[13]From January 15, 1999; joint appointment with DTM
[14]From January 11, 1999
[15]From August 16, 1998
[16]To September 1, 1998
[17]From July 24, 1998
[18]From September 24, 1998
[19]To January 8, 1999; joint appointment with DTM
[20]From June 7, 1999
[21]From June 1, 1999
[22]To July 30, 1998
[23]From September 16, 1998
[24]From June 1, 1999; joint appointment with DTM
[25]To August 31, 1998
[26]To March 31, 1999
[27]From November 1, 1998 to March 31, 1999
[28]Deceased March 21, 1999

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THE DIRECTOR'S INTRODUCTION:
The Ever-Whirling Wheel of Change

> "...I FIND IT TO BE THE GENERAL METHOD OF NATURE, WHICH IS ALWAYS GOING FORWARD, AND CONTINUALLY MAKING A PROGRESS OF CHANGING ALL THINGS FROM THE STATE IN WHICH IT FINDS THEM IN AT THE PRESENT..."
>
> ROBERT HOOKE (1699)[1]

The study of nature, as the English physicist and geologist Robert Hooke observed, is the study of change. Galaxies form and interact, stimulating the formation of stars. As stars consume their nuclear fuel, their often violent death throes can trigger the collapse of nearby clouds of gas and dust, generating new stars. Accompanying the formation of many stars was the formation of orbiting planetesimals and planets. The former are preserved in our solar system as asteroids and comets, and the latter are now known from recent discoveries of planets around other stars to include objects several times more massive than Jupiter. Our Earth and other Earth-like planets formed from the accretion of solid planetesimals and retained sufficient internal energy, augmented by the energy of radioactive decay, to melt rock and deform the surface for eons thereafter. Volcanic eruptions and earthquakes, the modern manifestations of that energy, provide important clues to the processes by which the Earth transports heat and magma from its deep interior to the ever moving tectonic plates and the volcanic centers concentrated near plate boundaries. Life on Earth has been both a beneficiary and an agent of changes in the planet's atmosphere, hydrosphere, and upper crust.

These subjects form the core of the research enterprise at the Department of Terrestrial Magnetism. The 13 essays that follow, each by a member of the Research Staff, highlight aspects of recent work. They convey a flavor of staff interests and how those interests, too, change as new tools or discoveries reveal new questions and open fresh avenues for inquiry.



Shown from left are DTM summer research interns Kirsten Brandt (Earlham College), Patrick Kelly (Sidwell Friends High School), Lan-Anh Ngoc Nguyen (University of North Carolina), Kisha Steele (Howard University), Kaisa Mueller (University of Missouri, Columbia), Caleb Fassett (Williams College), and Jacob Bauer (Spring Hill College).

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Left: Close-up view of a sulfide inclusion in a diamond from the Orapa kimberlite in Botswana, obtained with an optical microscope and incident light. The sulfide inclusion lies within the white dashed lines at the center of a "rosette" of fractures that radiate from the inclusion. These fractures formed by decompression when the diamond was transported rapidly to the Earth's surface during the volcanic eruption of the kimberlite. The edge of the diamond is visible in the upper right. (Photo courtesy of Steven B. Shirey.)



DTM staff in front of the Philip H. Abelson Building, Broad Branch Road campus, October 1999. First row (from left): Richard Bartholomew, Roy Scalco, Lawrence Patrick, Roy Dingus, Pablo Esparza, Maceo Bacote, Pedro Roa, William Key, Brian Schleigh. Second row: George Wetherill, Teresia Nguuri, Kenneth Chick, Joakim Bebié, Jie Li, Jane Goré, Fouad Tera, Emilie Hooft, Sandy Keiser, Vera Rubin, Sean Solomon, Rosa Maria Esparza. Third row: Larry Nittler, Alan Boss, Stephen Kortenkamp, Patrick McGovern, Satoshi Inaba, Merri Wolf, John Lynch, Daniela Power, Nelson McWhorter, Laurie Benton, Alan Linde, Georg Bartels, Philip Janney, Daniel Kelson, Terry Stahl, Louis Brown, Jianhua Wang, Aaron Pietruszka. Last row: Janice Dunlap, Harri Vanhala, Matthew Fouch, Randy Kuehnel, Shaun Hardy, Conel Alexander, Paul Silver, Paul Butler, David James, Stephen Richardson, Ian Mac Gregor, Mary Coder, Timothy Mock, Lianxing Wen, John Graham.

Change, of course, characterizes those who study as well as the subjects of our investigations. Two important changes in our Research Staff occurred during 1999. François Schweizer, a member of the staff at DTM since 1981, left the department at the end of August to join the staff of the Carnegie Observatories. That same month saw the arrival of our newest Staff Member, Paul Butler, an astronomer whose specialty is the detection and characterization of extrasolar planets. Schweizer's final DTM essay, and Butler's first such piece, are both included here and illustrate how astronomy at DTM is undergoing its own metamorphosis.

The pace and feel of daily activities on this campus also evolved over the past year. There were several new additions to the pool of talented postdoctoral scientists in the department (see Year Book 97/98, pp. 59-69) as others departed for academic or research positions at other institutions. The first full year of a new director of our sister department, the Geophysical Laboratory, saw the scientific and infrastructural boundaries between the two departments continue to blur. One measure of these changes is that 10 members of the DTM Research Staff are now formal coinvestigators on externally funded projects involving collaboration between the two departments. This past summer, the research intern programs at the two departments were formally merged, and 15 bright young men and women from colleges and secondary schools around the country were immersed for 10 weeks in the research programs of the institution.

Even the boundaries between heretofore distinct scientific disciplines are warping and falling. Nowhere

is this locally more evident than through Carnegie's participation as a lead institution in the NASA institute for the newly amalgamated field of astrobiology, founded with no less audacious a goal than the "understanding of the origins, evolution, distribution, and future of life on Earth and in the universe." Working under the auspices of this institute, now in its second year, are six Staff Members from DTM and an equal number from the Geophysical Laboratory. Few of these individuals imagined themselves as contributing to the advance of the biological sciences as little as two or three years ago.

Robert Hooke's insightful generalization of three centuries ago may be more encompassing than even he imagined.

—Sean C. Solomon

Virgo Cluster Galaxies with Disturbed Kinematics, and the Cluster Approach to Equilibrium

VERA C. RUBIN

We live in an era in which galaxies are forming into clusters. In a galaxy cluster, the high central galaxy density overcomes the expansion of the universe, and the galaxies are not separating, one from the other, but are gravitationally bound to the group. Some clusters, formed early, appear to be in dynamical equilibrium, with a deep central potential, massive elliptical galaxies in the core, and a fairly smooth spherical distribution of constituent galaxies. Younger clusters, like our nearby Virgo cluster, still contain irregular clumps of galaxies, which are expected to smooth out during their consequent evolution.

It has long been known that the Virgo cluster galaxies exhibit a curious distribution of central velocities when the galaxies are separated into ellipticals and spirals. The ellipticals, a population probably well on their way toward dynamical equilibrium, exhibit a Gaussian distribution of observed velocities with many velocities near 1,100 km/second. In contrast, the spirals have velocities that range equally from about -400 km/second (i.e., approach with respect to the cluster mean velocity) to about +2,600 km/second (i.e., recession). Hence the cluster, well defined by the ellipticals, is poorly defined by the spiral velocities.

Over the past decade, I have observed internal rotational velocities for the ionized gas component in 100 spiral galaxies in the Virgo cluster. Together with high school student Andrew Waterman and Yale University astronomer Jeff Kenney, I have analyzed these data. We divide the spirals into two groups, roughly equal in number: those with normal rotation properties, and those with significantly disturbed rotation. Independent of galaxy rotation properties, parameters such as galaxy brightness and Hubble type are the same for both groups.

However, the central velocities are strikingly different. Spirals with normal rotation curves have central velocities distributed evenly from -400 to +2,600 km/second, like the previously known spirals. In contrast, spirals with disturbed rotation have a distribution of central velocities that matches, almost exactly, the velocity distribution of the ellipticals (Fig. 1). Moreover, the distribution on the sky of the galaxies with disturbed rotation shows that these galaxies are preferentially on elongated radial orbits, which carry them close to the central core of the cluster. Here, tidal interactions are strong and more common.

We believe that the disturbed rotation properties arise from galaxy-galaxy or galaxy-cluster field interactions. Galaxies with disturbed rotation have

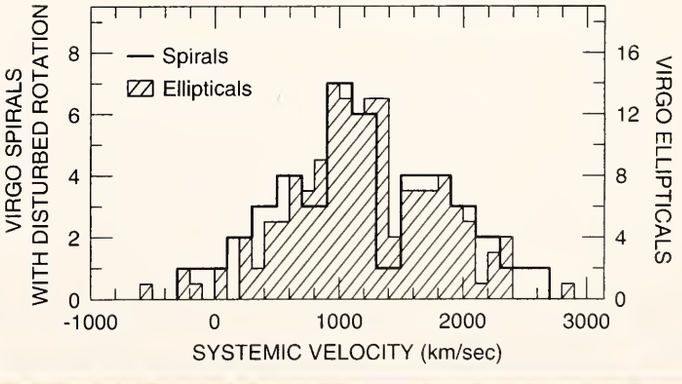


Fig. 1. The distribution of 43 spirals with disturbed rotation curves, as a function of systemic velocity, are superposed here on a histogram that shows the distribution of 164 ellipticals in Virgo. Note the exceptional similarity. (Elliptical velocities from the work of John Huchra of the Harvard-Smithsonian Center for Astrophysics.)

likely endured such an interaction within the last billion years. Interactions and mergers will alter the morphology of some galaxies, puffing the disks into a spheroidal or an elliptical morphology. The interactions will also play a role in driving the Virgo cluster toward dynamical equilibrium.

Star Clusters as Chronometers of Galaxy Evolution

FRANÇOIS SCHWEIZER

Many galaxies form and grow in fits and spurts. Periods of relatively tranquil evolution are punctuated by occasional collisions and mergers, during which a significant fraction of a galaxy's gaseous content can be violently compressed and turned into billions of new stars. These stars tend to form not only in isolation, but also in clusters that contain from a few to a few million stars. As observations with the Hubble Space Telescope have revealed, the most massive and dense of these newborn clusters survive even fierce mergers and appear as aging globular clusters, akin to the splendid but much older globulars that adorn the halo of our own galaxy.

The newborn globular clusters have three properties that make them near-ideal chronometers for studying galaxy evolution: (1) they are highly luminous and easily identified even in distant galaxies; (2) their stars are coeval, producing spectral signatures whose time evolution is well understood; and (3) their expected lifetimes are comparable to, and often exceed, the age of the universe. Hence, like tree rings, the age distributions of such clusters contain valuable clues about the past star-formation history and growth of the host galaxies.

Clusters between 100 million and 1 billion years old are relatively easy to date because their spectra feature strong, age-sensitive absorption lines due to hydrogen. Thus, the several hundred young star clusters discovered with Hubble in NGC 7252, a galaxy formed from two recently merged spirals, offer a rich sample for investigation.

For several years I have, in collaboration with others, dated most of these clusters from their measured colors and a few from their spectral absorption lines. The spectral method is the most accurate and yields cluster ages of 400-600 Myr (million years), telling us that vehement star formation occurred during a 200-Myr time interval beginning about 170 Myr after the close collision that started the galaxies' merger.

During the past year, we extended our efforts at deriving merger chronologies from cluster ages to both a younger, still ongoing merger and a suspected several-billion-year-old remnant. In collaboration with a team led by former DTM fellow Brad Whitmore (now at the Space Telescope Science Institute), we analyzed Hubble images of The Antennae, a spectacular pair of colliding spirals that have given birth to over 1,000 clusters so far. Our observations reveal peaks in the age distribution of the young clusters at about 500, 100, and less than 10 Myr, apparently reflecting the episodic nature of star-formation bursts in this still accelerating merger.

Among the youngest globular clusters some are truly gigantic, such as the 7-Myr-old "Knot S" depicted in Figure 2. This cluster dwarfs the most massive globular of our galaxy, ω Cen, by factors of 7 in size and 200 in luminosity. If placed at

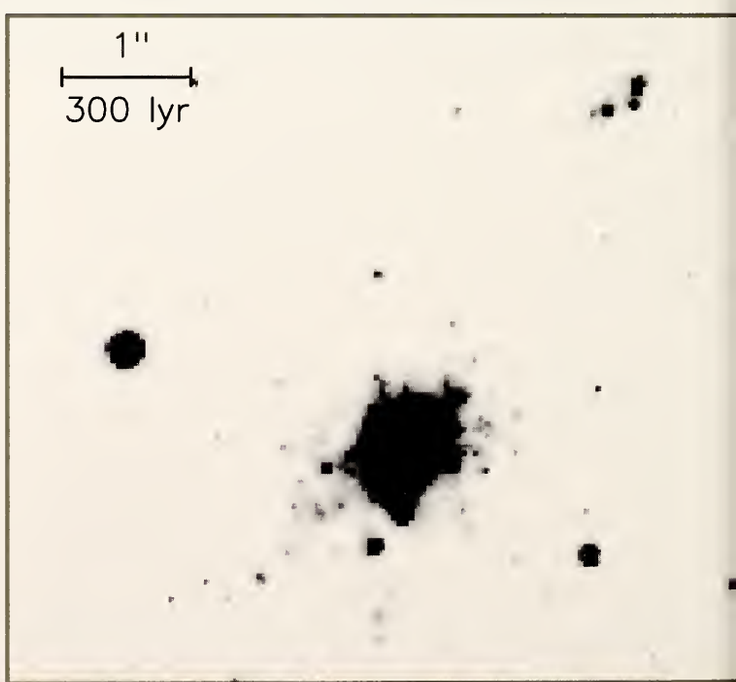


Fig. 2. Young globular cluster "Knot S," in The Antennae Galaxies, is imaged here with the Hubble. This huge cluster's outskirts extend beyond the image boundaries.

ω Cen's distance, Knot S would appear 7° in diameter, 10 times brighter than the Large Magellanic Cloud, and peppered with dozens of fifth-magnitude stars. This cluster's glory may, however, be short-lived. As it ages the stars will fade, and its huge envelope—currently extending over nearly 3,000 light-years—may be whittled away by tidal forces. Hence, over the next 10 billion years Knot S may still come to resemble ω Cen in luminosity and size.

At the other end of the age scale, some of the globular clusters in the elliptical galaxy NGC 3610 seem to show weak but measurable signs of similar former glory. In April 1999, we obtained—in collaboration with Jean Brodie of Lick Observatory, her student Linda Schroder, and Patrick Seitzer of the University of Michigan—exploratory spectra of seven clusters with the Keck II telescope on Mauna Kea. Though the data reduction is still in progress, two of the seven clusters already seem to show enhanced absorption lines due to hydrogen, suggesting ages of only 1.5-3 billion years. If confirmed by our planned follow-up observations, this would make NGC 3610 the first elliptical known to possess intermediate-age globular clusters and would add to other evidence that it formed from a major merger a few billion years ago. The new generation of large telescopes, and Magellan I and II in particular, will—I hope—greatly facilitate the unraveling of galaxies' star-formation histories from the fossil record contained in their globular clusters.

Star Formation in Radio Galaxy Centaurus A

JOHN A. GRAHAM

I am currently engaged in studying star formation occurring under unusual circumstances in the nearby radio galaxy Centaurus A (Cen A). I am working on this project with Caleb Fassett, who was a summer intern at DTM in 1999 and is now at Williams College. The radio emission from giant galaxies such as Cen A fills an enormous volume, making them among the largest objects in the universe. Located about 10 million light-years from us, the whole Cen A structure stretches over several degrees in the sky. Maintaining the huge energy output over astronomical timescales has always been a problem, and it is currently believed that they are powered by particle jets, which stream at relativistic velocities from the central core of the galaxy.

Cen A, although close, is a comparatively mild example of the class, and the radio jet is directly observed only close to the active nucleus of the galaxy. Farther out, it makes its presence known by impacting a stray cloud of dust and gas. Some of the gas is entrained in the jet and shocked into visibility by the impact. It is seen as a long stream of faint filaments (Fig. 3). The cloud is probably quite clumpy, and some material is compressed by the impact to the extent that gravitational cloud collapse is triggered and loose chains of young, luminous blue stars are formed. I have discussed characteristics of the gas in a recent paper, and the ongoing work with Fassett consists of obtaining brightnesses and colors of the blue stars as a means for estimating their ages and predicting their ultimate destinies.

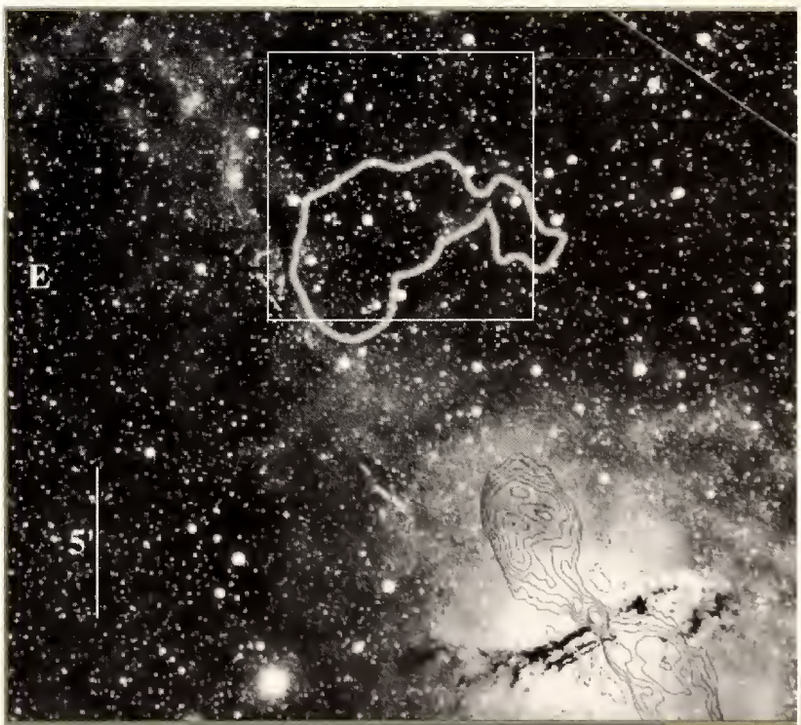


Fig. 3. The radio galaxy Centaurus A is shown with contours of the inner radio structure at 1407 MHz superposed. The outer radio lobes extend far beyond the confines of this illustration. The direction of the radio jet is indicated by the orientation of these inner radio lobes. Shown as a single broad white contour is the outer boundary of a neighboring cloud of dust and gas. Note the extended filamentary emission from gas entrained and excited by the radio jet. The square box shows the location of a region where shock-triggered star formation is observed.



Fig. 4. This image shows the southeast quadrant of the square field in Figure 3 showing loose groups of young blue supergiant stars that have formed at the edge of the cloud (bottom left and above center). Most of the bright stars in the field are foreground stars belonging to our own Milky Way galaxy.

The field we are investigating is outlined by the square in Figure 3. We use images taken with a 2,048 x 2,048 CCD detector on the du Pont 2.5-m telescope at Las Campanas Observatory. Images were obtained with *U, B,* and *V* filters to obtain color information. A blue image, shown as Figure 4, indicates the locations of the main concentrations of blue stars. Reduction of the observational material has been carried out with the software developed for the Hubble Space Telescope Key Project on the Distance Scale of the Universe (see Freedman entry in the Observatories' section). The brightest blue stars in the loose groups are close to magnitude 20 and are evidently quite normal and similar to the brightest stars in the Large Magellanic Cloud. Ages can be computed by interpolation of theoretical stellar models. A significant age range is indicated, extending from less than a million to more than 15 million years.

To maintain the observed energy in the radio lobes, the radio jet must be long-lived, with a lifetime of many millions of years at least. We thus have the unusual situation in which shocked gas and the stars resulting from triggered cloud-core collapse can be seen at the same time. In the more local situation in our galaxy, star formation is believed to be triggered by shocks generated in supernova outbursts. In such a case, however, the supernova, its remnant, and the attendant shocks have long disappeared by the time the new stars manifest themselves about a million years later. In Cen A, in contrast, because of the long life of the radio jet, we can see both the triggering mechanism and the consequent star formation at the same time.

Upsilon Andromedae and Multiple-Planet Systems

PAUL BUTLER

The rich diversity of planets in the solar system display an astonishing range of environments, from surface temperatures high enough to melt lead on Venus to the frozen rings of Saturn. Yet to first order, one can accurately describe the solar system as consisting of the Sun, Jupiter, and some leftover debris. If alien astronomers are looking at the solar system with technologies similar to our own, they will detect only the Sun and Jupiter. It is therefore not surprising that the first rush of extrasolar planet discoveries have all been of single-planet systems.

Over the last four years, about 30 planets have been discovered orbiting nearby Sun-like stars (Fig. 5). My collaborator Geoffrey Marcy, of the University of California at Berkeley, and I have found two-thirds of these using the "precision Doppler technique." An orbiting Jupiter-mass planet will gravitationally tug its parent star in a small counter orbit. This stellar wobble can be detected via the Doppler effect acting on the star's light. The planets discovered to date have orbital periods of a few days to a few years, and most of these planets reside in eccentric orbits. None of these planets reminds us of our own solar system, with giant planets in elegant circular orbits with periods of a decade or longer. And none of the systems found prior to 1999 has yielded more than one planet.

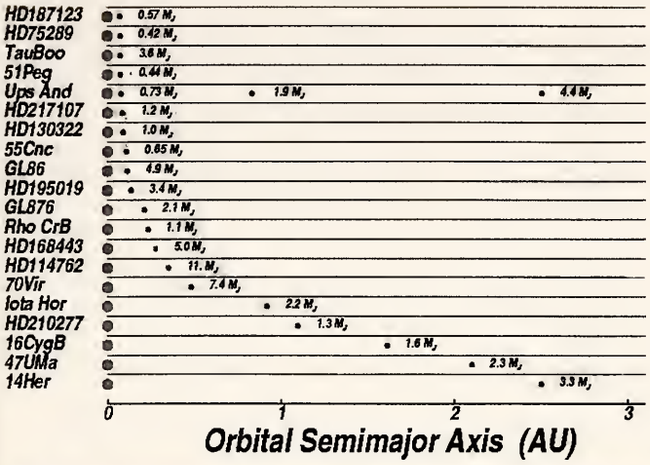


Fig. 5. Known extrasolar planets are shown as a function of orbital distance.

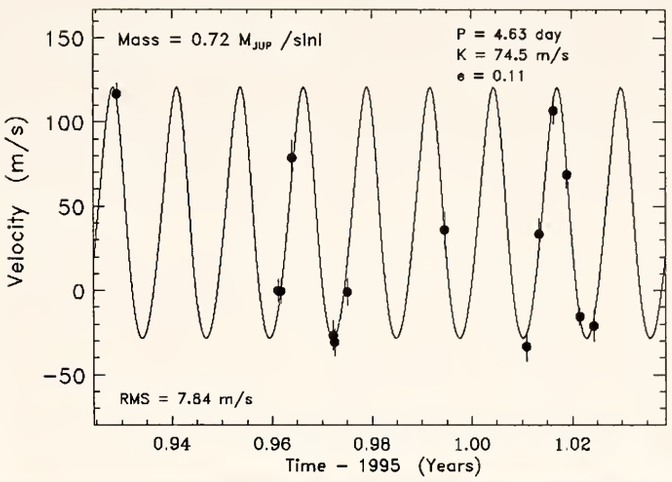


Fig. 6. These are the discovery data for the inner planet with a 4.6-day period in the Upsilon Andromedae system, from December 1995 to January 1996.

The discovery of a true multiple-planet system with current state-of-the-art technology requires a combination of measurement precision, patience, and luck. Reliable detection of an extrasolar planet by the precision Doppler technique requires that observations span a time covering at least two orbits. Since the longest-running precision Doppler program is only 12 years old, systems in which the outer planet has a period longer than 6 years would not yet be detectable. With this limitation, only those systems of multiple Jupiter-mass planets orbiting within 4 AU (1 astronomical unit = Earth-Sun distance = 93 million miles) of the parent star can be detected.

Upsilon Andromedae, the only confirmed system of multiple extrasolar planets, meets these conditions. Marcy and I have observed Upsilon Andromedae at Lick Observatory for the past 12 years. In June of 1996, we announced the presence of a planet in a scorching hot, 4.6-day orbit with a minimum mass of 0.7 Jupiter-masses (Fig. 6). Like the handful of other "51 Peg-like" planets with orbital periods of less than 5 days, the orbit is circular. The discovery paper noted evidence for additional longer-period planets.

Because of these suspicions, the Lick group and the Advanced Fiber Optic Echelle (AFOE) group (led by Robert Noyes at Harvard) independently monitored the Doppler velocity of Upsilon Andromedae as often as possible. By early 1999, more than 140 observations had been collected, allowing the complicated pattern of Doppler velocities to be untangled into two additional planets (Fig. 7). The middle planet in this system has 2 Jupiter-masses in a 240-day orbit; the outer planet has 4 Jupiter-masses in a 3.5-year orbit. Both the outer two planets are in eccentric orbits, as are all of the extrasolar planets that orbit more than 0.2 AU from their host stars.

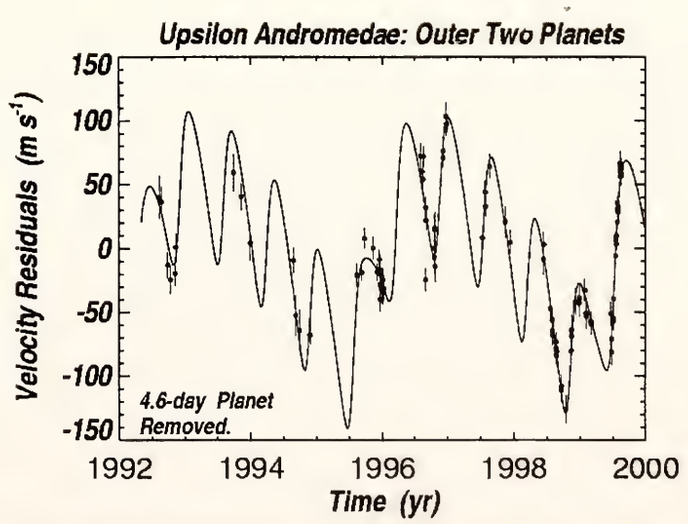


Fig. 7. The discovery data for the outer two planets in the Upsilon Andromedae are shown here, with the Doppler velocities of the inner planet removed.

With the possible exception of the companion to 47 Ursae Majoris, all of the extrasolar planets found to date are either "51 Peg-like" or eccentric. In the Upsilon Andromedae system we have both types of planets, perhaps making this a Rosetta stone that will allow us to understand the formation and evolution of these alien planetary systems. As the existing Doppler survey programs improve their precision, time baseline, and sample size, many more multiple-planet systems will be found.

Over the next 10 years, the precision Doppler technique will continue to provide the bulk of the extrasolar planet discoveries. Within the past three years, Marcy and I have increased the size of our survey from 100 stars to 1,100 stars using telescopes in both the northern and southern hemispheres, including the biggest telescope in the world—the 10-m Keck. By 2010 these surveys will provide the first hints about the fraction of planetary systems similar to the solar system, with giant planets orbiting out to 5 AU and beyond. These surveys will ultimately point the way to advanced technology missions (such as the proposed NASA Terrestrial Planet Finder) that will directly image Jupiter-like and Earth-like extrasolar planets, and ultimately take their spectra.

Rapid Gas Giant Planet Formation

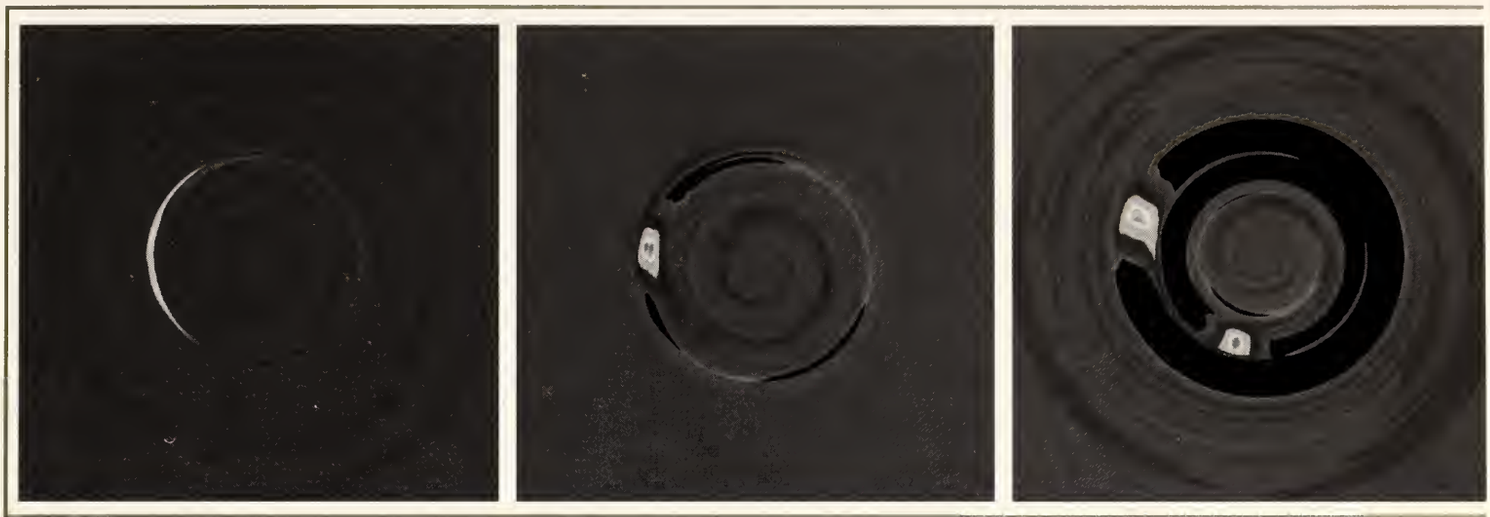
Alan P. Boss

As noted above, over two dozen gas giant planets have been detected in orbit around nearby stars, most of them discovered by Paul Butler and his colleagues. These discoveries have highlighted the unsatisfactory state of our knowledge about how gas giant planets like Jupiter formed. Two mechanisms have been suggested for forming gas giant planets, core accretion and disk instability. Core accretion is the generally accepted mechanism, but if disk instability is possible, it will occur well before core accretion can even get started.

The core-accretion model of giant planet formation presumes the collisional accumulation of a roughly 15-Earth-mass core of ice and rock, which then accretes hydrodynamically an envelope of hydrogen and helium gas. However, recent models of the interiors of Jupiter and Saturn require considerably smaller core masses than were previously thought, or even no core at all. Given the additional difficulty of growing a Jovian-mass planet within the expected lifetime of the solar nebula (a few million years at most), it seems prudent to investigate other mechanisms for giant planet formation as well.

The only viable alternative appears to be the disk-instability mechanism, where a gravitationally unstable disk breaks up into clumps of gas and dust that can contract and become giant gaseous protoplanets. The disk-instability mechanism can lead to core formation by rapid sedimentation of dust grains as the protoplanet slowly contracts toward planetary densities. Because the instability occurs over a timescale of about 1,000 years, there is no danger of losing the disk gas before the giant gaseous protoplanets form. However, the instability requires a disk that is massive enough and cold enough to become gravitationally unstable. Disk instability may be able to explain the formation of massive giant planet systems like that of Upsilon Andromedae, described by Paul Butler.

In order to study further the disk-instability mechanism, I have calculated the evolution of a number of three-dimensional (3D), gravitational-hydrodynamical models of protoplanetary disks starting from realistic initial temperature and density profiles. The 3D models show that a clump-forming disk instability can occur in marginally unstable disks with masses as low as 4% of a solar mass inside a radius of 10 AU and perhaps even in disks with somewhat lower masses. However, the disk mass seems to need to be greater than about 1% of a solar mass inside 10 AU. Models with doubled radial extent show that the outer boundary conditions on the calculations have little effect on the results. This implies that clump formation may be limited to an annulus in orbital radius between about 5 AU and 12 AU, with the usual outcome being two multiple-Jupiter-mass clumps within this annulus (Fig. 8). These 3D models suggest that a protoplanetary disk with a mass at the high end of the range (1% to 7% of a solar mass), considered possible for the minimum-mass solar nebula, could quickly lead to the formation of two



Equatorial density after 2,200 years is shown for a disk with a mass 10% that of the Sun. The region illustrated has a radius of 20 AU. The surface density in this relatively low-mass disk is comparable to that required for runaway accretion in core accretion models. The lightest area is highest density. Spiral arms have grown and are being sheared by differential rotation into thin filaments.

This image shows the equatorial density after 3,000 years for the same disk. The spiral arms have grown around 8 AU and have formed a double clump. These clumps are sweeping up the gas at their orbital radius, forming a thin gap (black arcs). The two clumps soon thereafter merge. A solar-mass protostar wobbles unseen at the center of the disk in reaction to the clumps.

Equatorial density after 3,500 years is seen for the same disk, about 17 orbital periods (at 10 AU) later than the previous figure. The first clumps have helped stimulate the growth of another clump with a radius of around 7 AU, and the merged first clump has moved outward to 10 AU in response. Both clumps have cleared wide gaps in the disk, and should contract to form gas giant planets with initial orbital radii similar to those of Jupiter and Saturn.

Fig. 8

giant gaseous protoplanets, one at about 6 AU and one at about 12 AU. The terrestrial and outer planets could then form much later by the usual process of collisional accumulation of solids, a process that has been studied in most detail by George Wetherill.

Disk instability thus seems to be possible in disks with total masses comparable to that inferred for the solar nebula, and indeed comparable to the disk masses that seem to be required in order for core accretion to produce giant planets in a few million years. Clearly if a disk instability can occur, it will outpace core accretion.

Formation of the Asteroids

GEORGE W. WETHERILL

On the same day that I sat down to write this brief essay, I learned by e-mail of the death of the Russian astronomer Victor Safronov, who during the 1960s created the modern epoch in the study of the physical processes by which planets are formed. I wouldn't be doing this work if it had not been for his inspiration. One of his minor contributions was to introduce the biological term *embryo* to describe the bodies that were to grow into planets. This tradition can be extended to describe the development of this science itself. It has passed through the stages of infancy and childhood, when these processes seemed relatively easy to understand. On the way to maturity, we are now experiencing a confusing and difficult period of "adolescence," in which nothing seems to work as well as it did a decade earlier. Ironically, this is a natural consequence of the great advances that have been made in understanding the dynamic processes involved, the ability to test complex models with readily affordable desktop computers, the new theoretical and observational discoveries in the area of star formation, and the first actual observation of the planetary systems of other stars, a field in which our new Staff Member, Paul Butler, is a pioneer. Many enigmas have been revealed by these more advanced discoveries.

A major difficulty is that in our solar system all of these events took place 4.5 billion years ago. All of

the larger planets have experienced major changes since their formation, and even for the Earth, the only planet that has been studied in much detail, the essential record of its earliest history has been very badly obscured by later events. Thus the planets provide little "ground truth" for testing theories.

Nevertheless, well-preserved samples of rocks that were formed within the first few million years of the formation of our Sun are readily available and are being studied by use of precise technology in laboratories throughout the world, including the isotope cosmochemists in this department. These samples are the meteorites. A small number of these are known to be rocks blasted from the Moon and Mars by impacts of asteroids and comets. The great majority are fragments of asteroids themselves. Asteroids are small planets, ranging up to about 1,000 km in diameter. Most of their orbits lie between those of Mars and Jupiter. Because of their small size, they have been spared the geological processes that have obscured the early history of the larger planets. As a result, they still have a "memory" of the circumstances under which they and the other planets were formed.

It is not possible to simply "invert" the meteoritic data and infer events in the early solar system. Rather, it is necessary to "forward model" quantitative alternative plausible scenarios of asteroid formation, and compare the consequences of these models with the record preserved in the meteorites.

Rather little attention has been given to this opportunity. One such study is an extension of earlier calculations I published in 1992. These have now been repeated by the use of greatly improved computational facilities, as well as software developed by a former DTM postdoctoral associate, John Chambers, who is now on the staff of the Armagh Observatory in Northern Ireland. This work has been published during the past year. Chambers and I have written a paper concerning the processes in the asteroid region during the early solar system. It examines the consequences of the "standard model" of planet formation and shows that not only the inner planets, but unobserved planets in the asteroid region as well, would grow to about the size of Mars in less than a few million years. In this standard model, Jupiter and Saturn become gas giant planets somewhat later. We then find, thank goodness, that gravitational interactions between these "asteroid planets" and Jupiter and Saturn quickly remove these presently nonexistent large bodies in the asteroid region, leaving only residual small bodies that represent the observed asteroids, the sources of the meteorites.

At the same time, present DTM postdoctoral associate Stephen Kortenkamp and I are developing an alternative model to permit comparison with these consequences of the standard model. This model makes use of the computations made by Alan Boss that imply that the giant planets discovered by Paul Butler and others could have formed very rapidly, during the later stages of the formation of their central star. Boss has suggested that Jupiter and Saturn may have formed by this same mechanism (see above), thereby avoiding some serious difficulties with the standard model. We are also examining whether this alternative model also permits the formation of small asteroids and the inner terrestrial planets. At present our answers to these questions are "maybe" and "probably." We are trying to provide better answers and to infer the consequences of such alternative models, with regard to the unique information preserved in the meteorites, as well as their asteroidal parents that are at present targets for observation by spacecraft.

The Formation of Chondrules

Conel M. O'D. Alexander

At 4.55 billion years in age, chondritic meteorites are the oldest known rocks in the solar system. When looked at in detail, they appear to be essentially sedimentary rocks and are made up of primitive materials that formed in the first 10 million years or so of the solar system. This was when the solar nebula—the disk of gas and dust that surrounded the young Sun—was still present and dust was beginning to accumulate into planets. If we can only decipher them, chondrites will provide us with a window into processes that occurred in the nebula during this important but distant period.

The most abundant of the materials in chondrites (50-80% by volume) are chondrules. These are millimeter-size spherical objects that appear to have formed as free-floating molten droplets in the nebula. Melting material with their compositions requires temperatures of 1500-1800°C. Clearly the process that formed them was very energetic. If their abundance in chondrites is any guide, chondrule formation was one of the most energetic processes in the nebula, at least in the region of the asteroid belt between Mars and Jupiter where the chondrites come from.

Despite having been studied for over 100 years, there remains no consensus on what the energy source was for making chondrules. More progress has been made in trying to pin down the conditions under which chondrules formed, however. Simulation experiments of chondrules suggest that they were rapidly heated to near their total melting temperatures (1500-1800°C) and then cooled at 100-1000°C/hr. The cooling rate of a millimeter-size droplet radiating freely into space at such high temperatures would be at least 100 times faster than these estimates. To slow the cooling rates probably requires that the chondrule-forming regions were fairly large and dusty. How large and how dusty remains very uncertain.

At present, we have few independent means of determining conditions in the nebula, such as dust densities or gas pressure, and we must rely on astrophysical models for estimating them. Pressures in the nebula were probably low, about 10^{-3}-10^{-6} atmospheres. At these pressures and at the high temperatures of chondrule formation, many elements become volatile. The degree of volatility of some elements can be very sensitive to the conditions, such as gas pressure. Therefore, it might be possible to constrain nebular conditions if we can determine the degree of volatile loss of one or more elements. During evaporation, the heavy isotopes of an element become increasingly enriched in the residue, in this case the chondrule. The isotopic composition of an element can therefore be a sensitive indicator of the degree of evaporative loss. I have been developing techniques for making precise isotopic measurements of four elements, potassium, iron, magnesium, and oxygen. These elements will have had quite different volatilities during chondrule formation.

The potassium and iron isotope measurements were made with the DTM's ion microprobe in collaboration with Jianhua Wang. The magnesium isotopes were measured with the DTM's new Plasma 54 multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS) in collaboration with Richard Carlson, Timothy Mock, and summer intern Lan-Anh Nguyen. Joint DTM-Geophysical Laboratory-Smithsonian Institution fellow Richard Ash made the oxygen isotope measurements with the laser fluorination system developed by Douglas Rumble.

The picture that emerges from these four elements is still hazy. The two most volatile elements, potassium and iron, show no evidence of evaporative loss; the more refractory magnesium exhibits isotopic fractions consistent with small degrees of loss; and oxygen seems to have undergone isotopic mixing between two reservoirs with quite different isotopic compositions but not the isotopic fractionation associated with evaporation. There are conditions under which the fractionation associated with evaporation can be suppressed in some elements. The challenge is to explain the results for all four elements, a task that will require detailed numerical modeling.

Coupling between Climate Change and Tectonics on Venus

SEAN C. SOLOMON

Planets have considerable internal energy, and the processes of energy transport and loss drive long-term changes. Understanding the differences in evolution among the planets of our solar system poses a considerable challenge. A particularly interesting puzzle has been Venus, in size and in bulk composition the planet most similar to Earth. One important difference in the two planets is their climates. The dense carbon dioxide atmosphere and global cloud cover have turned Venus into an efficient greenhouse, trapping solar radia-

tion and rendering the modern surface temperature a searing 740 K. Another difference is in their volcanic and tectonic history. Lacking Earth-like plate tectonics, Venus shows evidence for widespread resurfacing of the planet about 500 million years ago as well as globally coherent episodes of deformation that appear to have been concentrated over short intervals of the preserved geological history. Recent work of mine, carried out with collaborators Mark Bullock and David Grinspoon at the Southwest Research Institute, suggests that these two aspects of the evolution of Venus may be strongly coupled.

Bullock and Grinspoon have shown that the climate of Venus is unstable with respect to a very large volcanic eruption, because such an event would release into the atmosphere significant quantities of water and sulfur dioxide from the erupting lavas. Water and sulfur dioxide are greenhouse gases that modify the radiative balance in the atmosphere; their abundance also affects strongly the distribution of sulfuric acid-water aerosols that make up the Venus clouds. There are important sinks for both species: photodissociation of water molecules and loss of hydrogen to space, and chemical reaction of sulfur dioxide with surface and near-surface minerals. Climate models incorporating all of these processes indicate that for a sufficiently large eruption the excursions in surface temperature accompanying changes to the greenhouse and to the global cloud cover can exceed ±100 K and can extend over periods from tens to hundreds of millions of years.

Such temperature changes over these timescales diffuse deep into the interior of a planet. Differential temperature changes of this magnitude expand or contract surface and near-surface material by amounts sufficient to fracture rock. Climate change on Venus is therefore capable of affecting the deformation of the surface and the global distribution of tectonic features.

We tested this idea by examining the climate change that would have followed the emplacement of the largest distinct episode of widespread volcanism known to have occurred on Venus: the

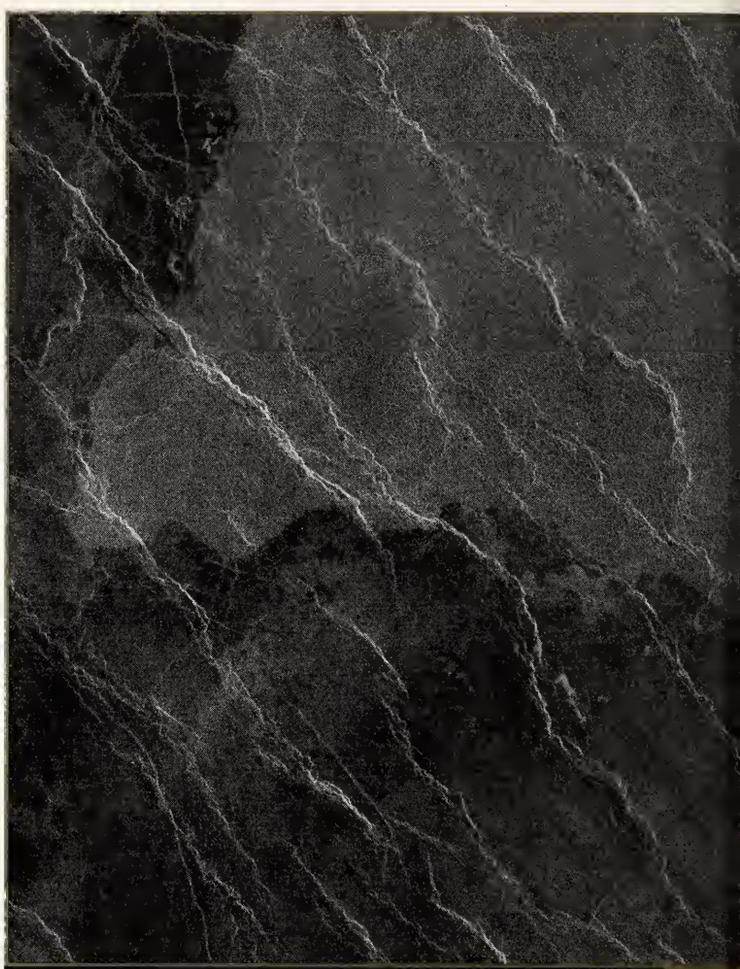


Fig. 9. A radar image of ridged plains is shown for Rusalka Planitia, Venus. The image is about 155 km wide. Northeast-southwest contraction has produced the radar-bright, northwest-southeast trending wrinkle ridges, which postdate plains emplacement.

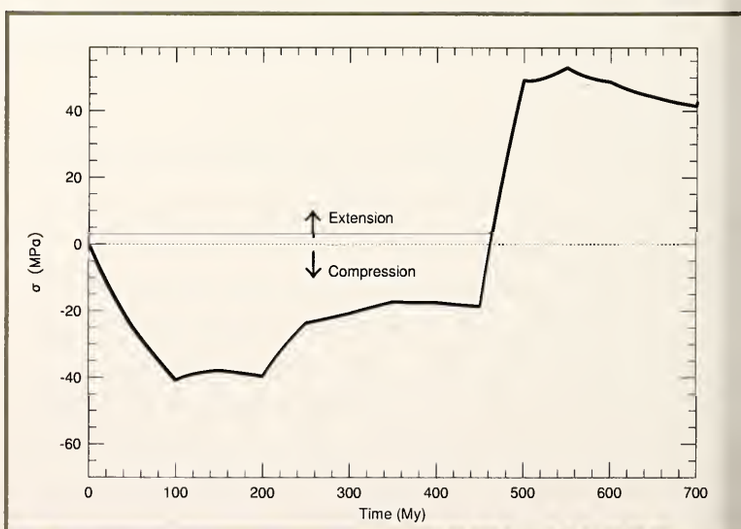


Fig. 10. The predicted evolution of surface horizontal stress resulting from the climate change that accompanied and followed emplacement of ridged plains lavas is depicted here. The compressive stresses that accumulated in the first 100 million years of the model would have been sufficient to produce widespread faulting manifested in the formation of wrinkle ridges.

eruption of the ridged plains. These plains, making up 60-65% of the present surface, are characterized by pervasive wrinkle ridges (Fig. 9), produced by horizontal shortening of the lithosphere. The volume of lavas that erupted to form the plains, on the basis of area and relief of buried topography, was at least 2×10^8 km^3, as much as an order of magnitude greater than even the largest of the major igneous provinces on Earth. Widespread ridge formation evidently occurred less than 100 million years after the plains were emplaced, on the grounds that only about 1% of impact craters on these plains have been deformed by the wrinkle ridges. The change in surface horizontal stress predicted to accompany the climate change that would follow eruption of the ridged plains lavas is of the correct sign and magnitude to account for a narrow interval of time between plains emplacement and wrinkle ridge formation (Fig. 10), as observed.

Many further tests are in progress. These include exploring the sensitivity of climate models to changes in key parameters, incorporating a fuller description of the known volcanic flux history of the planet, and exploring whether other apparently global episodes of coherent contractional or extensional deformation might also be the result of stresses induced by climate change. What is already apparent is that climate change on Venus has been much more pronounced than the "global warming" that heats political debates on this planet, and that the coupling between climatic and tectonic change may be a major contributor to the distinct evolutionary tracks of Venus and Earth.

Water in the Hawaiian Mantle Plume: Where Did It Come From and Where Did It Go?

ERIK H. HAURI

Water plays a highly significant role in the generation and differentiation of magmas in a variety of planetary environments. Water dissolved in minerals in the deep Earth can strongly lower both the melting temperature and the viscosity of rock. At high abundances, water can also determine, in large part, many of the physical properties of magmas that influence eruption dynamics. The presence of liquid water at the Earth's surface is also thought to be a primary factor that enables the persistence of active plate tectonics.

The primordial conditions under which the Earth formed were probably very hot, perhaps hot enough to have melted much of the planet. As a result, the Earth's interior was depleted in volatile elements during accretion and has lost volatile elements throughout its history by the eruption and degassing of magmas at locations of active volcanism. On other planets, the water expelled from volcanoes is either lost to space by a variety of physical and chemical mechanisms—such as on Mercury and Venus—or may be partly frozen as ice and trapped in the crust, as on Mars. However, temperature conditions on the Earth's surface favor the stability of liquid water. Geophysicists have long recognized the lack of active plate tectonics on the other terrestrial planets. This observation has led to the idea that water from the Earth's surface is carried into the interior by plate subduction and serves as the lubricant that facilitates plate tectonics. Water-rich explosive volcanism occurring at subduction zones confirms that water is carried down with the descending plate. But two major questions about the water budget at subduction zones remain unanswered: How much of the water that goes down into subduction zones comes back up at subduction-zone volcanoes, and how much water is left in the subducting plate that is carried into the deep Earth? The answers to both of these questions will constrain the amount of water that is left in the upper parts of the Earth's mantle to lubricate plate tectonics.

To address the second question about water trapped in the subducting plate, I am measuring the abundance and isotopic composition of water in magmas from the Hawaiian Islands. Our previous geochemical work on Hawaii has shown that certain Hawaiian volcanoes (Koolau, Mauna Loa, Mauna Kea) contain a component made up of recycled oceanic crust and sediment that had been carried into the deep mantle during an ancient subduction episode. Oxygen isotope work on these same samples, carried out with collaborators at the California Institute of Technology and the

University of Wisconsin, showed convincingly that these components had interacted with water near the Earth's surface. We therefore selected one of these volcanoes (Koolau) to initiate our study.

Magmas that erupt on the Earth's surface lose their water through degassing. Only those that erupted at ocean depths greater than 500 meters cool quickly enough to retain their original volatile contents. Another way of examining volatiles in magmas is to study tiny inclusions of melt, which are trapped in solid crystals that have grown from the magma before eruption. Because the crystal surrounding these inclusions acts as an inert capsule, melt inclusions can preserve a record of the behavior of volatiles deep within the volcanic system even when they are contained in lava samples that have erupted on the Earth's surface and lost their own volatiles. These inclusions have been measured for their volatile abundances (H_2O, CO_2, F, S, Cl) and hydrogen isotope ratios using the DTM ion microprobe.

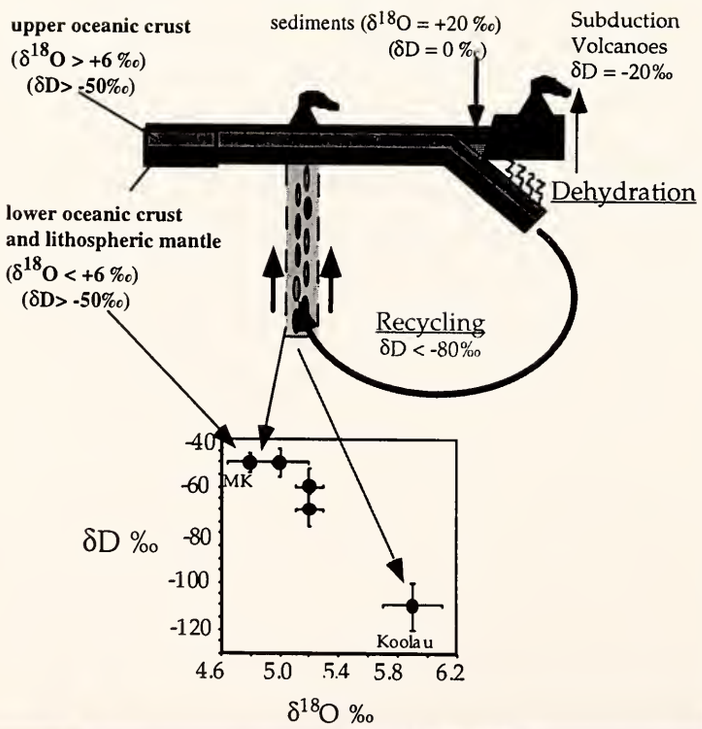


Fig. 11. The upper crust and lower crust of the oceanic plate interact with seawater at different temperatures, resulting in changes in their average oxygen and hydrogen isotope ratios. Addition of seawater-derived sediments (down arrow at top) adds material with high oxygen isotope ratios and high water contents. During subduction, some of the water is transported into the mantle source of subduction-zone volcanoes by dehydration, while the water remaining in the subducted plate is recycled (curved arrow) and returns to the surface in mantle plumes such as Hawaii. This cycle results in correlations between oxygen and hydrogen isotopes in Hawaiian magmas (inset).

The melt inclusion results for several Hawaiian volcanoes (Loihi, Kilauea, Mauna Loa) show moderate water contents and hydrogen isotopes, which generally agree with the data on submarine eruptions on these same volcanoes. The H_2O and Cl data on melt inclusions reveal that many magmas are contaminated by seawater-derived components prior to eruption, a process which changes their original Cl, H_2O, and hydrogen isotope compositions. The Koolau melt inclusions, however, are characterized by the lowest abundances of H_2O, S, and Cl ever observed for any undegassed Hawaiian magma, and these low abundances are coupled with the lowest hydrogen isotope ratios ever observed at Hawaii (Fig. 11). The combined volatile data sets for melt inclusions and submarine eruptions show a correlation of hydrogen isotope ratio with other isotopes measured on the same samples, including oxygen isotopes.

The lavas from the Koolau volcano contain the largest amount of the water-altered recycled oceanic crust component, yet they appear to have the lowest abundances of volatiles. This observation is best explained if the recycled plate was extensively dehydrated during the ancient subduction episode that introduced this component into the deep mantle. The observed hydrogen isotope ratios for Koolau are consistent with hydrogen isotope changes expected during dehydration of a subducting plate containing hydrous minerals. These observations lead us to conclude that subduction dehydration is very efficient, with the result that nearly all of the water that goes down into subduction zones is released from the descending plate and transported into the zone of magma generation beneath subduction-zone volcanoes. The amount of water left in the mantle after subduction-zone volcanism is probably the lubricating force for plate tectonics. How much is left? Answering this question will require similar ion-probe studies of melt inclusions from subduction-zone volcanoes.

Rhenium-osmium (Re-Os) Studies of Sulfide Inclusions in Diamonds from the Orapa Kimberlite, Kaapvaal Craton, Botswana

STEVEN B. SHIREY

Sulfides, chiefly of iron (Fe) but also with subordinate nickel (Ni) and copper (Cu), are common inclusion minerals in diamond that occur in two basic assemblages: peridotitic (p-type) and eclogitic (e-type). At DTM the recent development, by former fellow Graham Pearson, Richard Carlson, and me, of microchemical techniques for the analysis of the rhenium-osmium isotopic compositions of single sulfide inclusions at 10^{-15} gram levels has led to detailed geochronology on individual diamonds that contain either inclusion assemblage. Apart from the obvious economic importance of such work to diamond exploration, any materials encased in diamonds provide a unique geological sample of mantle minerals that have been isolated from chemical exchange since diamond growth. Diamond distribution on Earth is closely linked to the distribution of continental mantle keels. Thus, an important focus of this research is to compare diamond growth episodes to geological processes such as continental core (craton) stabilization and much later continent-margin accretion via subduction to understand the role of continental keels in continent development.

A Re-Os isotopic study of sulfide inclusions in diamonds from the 93-million-year-old Orapa kimberlite in Botswana is under way. The Orapa kimberlite is host to one of the world's largest and most productive diamond mines and is situated on the northwest side of the ancient continental core making up southern Africa called the Kaapvaal craton. Orapa is noted for its well-exposed kimberlite (the diamond host rock), its diamond-bearing and non-diamond-bearing eclogite (high-pressure metamorphosed basalt) xenoliths (rock fragments carried by the kimberlite), and the high proportion of sulfide and silicate in its diamond inclusion population. In general, we want to better understand the age spectrum of diamonds containing e-type sulfide inclusions at localities such as Orapa, where we can compare sulfide inclusion ages to previously studied eclogitic silicate inclusion ages. A goal is to look for other generations of diamond growth, and to explore the relationship between the sulfide inclusions in diamond and their eclogite xenolith hosts in ways that can be extended to the larger Kaapvaal craton and its geological history.

The sulfides fall into two groups based on the Re-Os isotopic data: one group with a 2,900-million-year age and the other with a 990-million-year age (Fig. 12). The older age represents the first firm Archean age for diamonds containing eclogitic materials. This is exciting because it begins to resolve the long-standing issue of why there have been good examples of old diamond-bearing eclogite xenoliths but few examples of old eclogitic diamond inclusions of either sulfide or silicate type. The younger age is interesting because it is identical to the previous 990 million-year-old samarium-neodymium isochron age obtained on Orapa eclogitic garnet and clinopyroxene diamond inclusions.

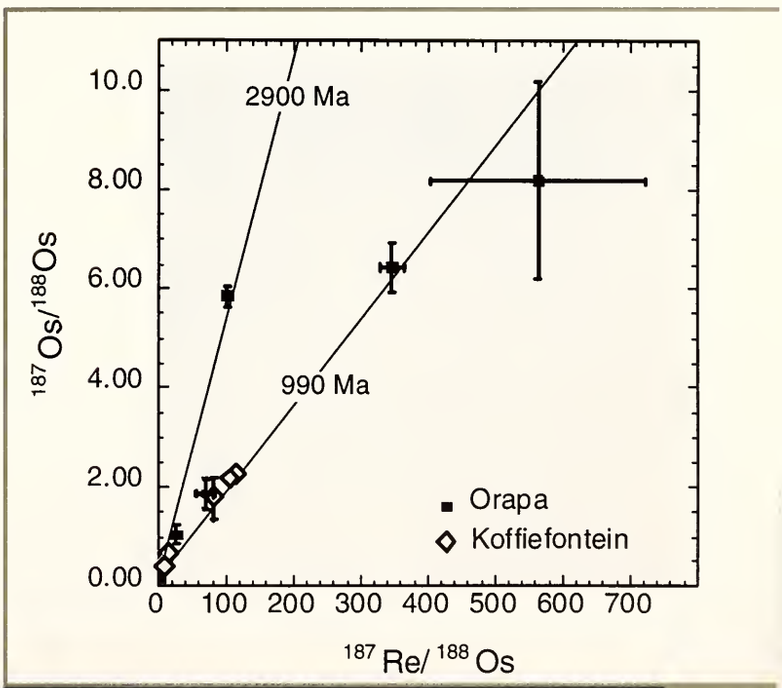


Fig. 12. This Re-Os isochron diagram shows Orapa and Koffiefontein eclogitic (e-type) sulfide inclusions in diamond. Each data point represents the inclusion from a single diamond. Error bars are derived chiefly from blank correction uncertainties when analytical concentrations of Os are low (e.g., 30-100 x 10^{-15} grams). Error bars are not shown when smaller than symbols. 990 and 2,900 million-year-old (Ma) lines are shown for reference purposes. (Koffiefontein data from Graham Pearson of the University of Durham and coworkers.)

These data suggest that there were at least two episodes of diamond growth in the mantle beneath the Orapa area, separated by about 2,000 million years. The striking similarity of the older ages to the rhenium-depletion model ages on peridotites from the Letlhakane kimberlite 40 km to the east-southeast of the Orapa kimberlite makes a compelling argument that continental core stabilization about 2,900 million years ago was accompanied by oceanic crustal underthrusting to make eclogite. The striking similarity of the younger ages to the eclogitic sulfide inclusions in diamond at the Koffiefontein kimberlite some 800 km to the south indicates that eclogite emplacement into the cratonic lithosphere 1,000 million years ago may be more widespread than previously thought.

Crustal Deformation and the DTM Borehole Strainmeter Program

Alan T. Linde

Earthquakes and volcanic activity result from changes within the Earth. Those internal changes also cause deformation of the Earth's surface. For a number of years, working with Selwyn Sacks, I have carried out a program of both measuring such deformations in tectonically active areas and interpreting the data in terms of processes at depth. The primary source of data for this program comes from Sacks-Evertson borehole strainmeters installed in a number of different active areas, particularly California, Japan, and Iceland. These high-resolution data have allowed identification of new processes, such as slow earthquakes in seismogenic zones and changes in magma reservoirs during episodes of volcanic activity, which are not detectable with other techniques.

Work on this program in the last year has resulted in the completion, or near completion, of several studies. With Icelandic colleagues Kristján Ágústsson and Ragnar Stefánsson, we analyzed strain changes associated with a moderate (magnitude 5.8) earthquake in southern Iceland. Coseismic changes were consistent with the earthquake's parameters determined from seismic waves and allowed resolution of spatial variation in the slip distribution. Preceding and following the earthquake were slow strain changes, which were interpreted as being due to magma movement. It appears that this earthquake may have been triggered by an episode of dike growth.

Our work on slow earthquakes, based on recordings from the strainmeters, led us to reexamine reports of slow changes before the great Tonankai (1944) and Nankaido (1946) earthquakes along the Nankai trough south of Honshu, Japan. The evidence for those slow changes came from leveling surveys, tide gauge records, and reports of the drying up of water wells. Because such changes have had significance in earthquake prediction efforts in Japan, we were interested to see if the slow changes were consistent with slow earthquakes before the main shocks. Our results show that such is the case and that the slow rupture takes place on the subduction interface down-dip from the seismic rupture zone. This situation, similar to what happened before the 1960 great Chile earthquake, is such that the slow events increased the shear stress in the seismogenic zone, presumably triggering the earthquakes.

New insight into volcanic activity has come from analyzing borehole strain data from sites close to Hekla, Iceland, and Long Valley, California. Sacks and I, together with colleagues Osamu Kamigaichi, Kenji Kanjo, and Masaaki Churei of the Japan Meteorological Agency (JMA), are analyzing the deformations caused by the 1986 eruption of Miharayama on the island Izu-Oshima in Japan. The strainmeters, which recorded that activity, are part of a network installed by the JMA as part of their earthquake prediction research program. The data show that, during the first stage of the eruption, the relatively shallow reservoir (which was the ultimate source of magma for the eruption) was continuously being replenished from a much deeper (about 30 km) source. Additionally, the rate of that replenishment was changed at the time of small volcanic earthquakes. Strain changes preceding the second stage of the eruption were clear at distances up to 50 km. Those strain changes were due to the formation and propagation of dikes from a depth of several kilometers up to the surface. Somewhat surprising was the fact that most of the magma movement from the reser-

voir was not to the surface but rather into a large dike that did not break the surface.

The strainmeter observational program continues to be enhanced. Over the next several years, in collaboration with the U.S. Geological Survey and the University of California at Berkeley and San Diego, about 10 new sites will be instrumented in California in the San Francisco Bay area. In the summer of 1999, borehole strainmeters together with tiltmeters and seismometers were installed for the first time in deep drill holes (about 1,100 m) below the seafloor, as described at greater length below. Data from these sites should yield new insight into the processes of plate motion and earthquake generation.

Strain Diffusion from Great Earthquakes

I. Selwyn Sacks

The motion of the plates in the uppermost Earth causes deformation that can lead to failure at the interaction boundaries. The deformation results in the slow buildup of stresses, but those stresses can be released rapidly and possibly catastrophically as earthquakes. Recent observations, initially from high-sensitivity borehole strainmeters, showed that these failures can also occur slowly on the same faults that have regular destructive earthquakes. The residual stress and the proximity to failure, therefore, cannot be estimated without knowledge of these slower events. The analyses of data from slow events and from volcanic eruptions are discussed further in the article above by Alan Linde.

Also important is another type of slow deformation of the Earth's surface due to strain diffusion from great earthquakes, volcanic eruptions, or spreading events at the separating plate boundaries. This type of deformation propagates across the surface at velocities that depend on the distance from the source. Near the source, the propagation velocity is some hundred kilometers per year, but at greater distances the velocities decrease to only a few kilometers per year. The parameters of the elastic crust and those of the viscoelastic underlying layers govern this highly dispersive propagation rate. Analyses of this slow deformation have allowed determination of the viscosity of the crust and uppermost mantle for Japan, California, and Iceland. Some of these deformations can be measured hundreds of kilometers from the source even after a century. An important consequence of this long-lasting disturbance is that the present-day strain field, even from highly precise Global Positioning Satellite (GPS) measurements, cannot be reliably estimated without allowing for the effects of past great earthquakes.

Another key effect of this strain diffusion has recently been recognized. The slowly propagating strain pulse is capable of unlocking favorably oriented, highly stressed faults. It does this by reducing the force pressing the two sides of the fault together, allowing the fault to slip in an earthquake. Former DTM fellow Fred Pollitz and I have shown that the highly destructive 1995 earthquake in Kobe, Japan, was likely triggered by strain diffusing from great earthquakes in 1944 and 1946. And the Tonankai earthquake of 1944, which occurred about 50 years earlier than expected, may itself have been triggered by strain from a great earthquake in 1891. Because of the orientation sensitivity, strain pulses are also capable of inhibiting earthquakes. Since in many active tectonic regions there are faults with many different orientations, it is possible to calculate the probabilities that for any particular fault the likelihood of failure has been enhanced or lessened. In a region in south central Japan, Pollitz and I found that during the period 1901-1969, all earthquakes occurred where the failure probability was enhanced by strain diffusion, mainly from the 1891 Nobi earthquake. No earthquakes occurred where the fault orientation was such that the strain pulse increased fault clamping even though many of these faults have been similarly active historically.

While the physics of strain diffusion is reasonably well understood, earthquake rupture at slow speeds is not. In particular the discovery by Alan Linde and me, that slow events can occur on the same faults that also fail rapidly at other times, is yet to be understood. It is obviously of considerable societal relevance to understand what conditions cause the different behavior. One of the most dramatic

situations occurs off northeast Japan. Here there are great subduction events, as large as magnitude 8. However, most of the plate motion is released as slow, non-destructive events that, until recently, could not even be detected. The locked zone of these earthquakes is well to the east of Japan, so can best be studied using instruments on or below the seafloor.

During the summer of 1999 a DTM team—Linde, Nelson McWhorter, Ben Pandit, Michael Acierno, and I—spent two months on the drill ship of the international Ocean Drilling Program, the *JOIDES Resolution*, about 120 km off the coast of Japan. Two holes, about 50 km apart, were drilled and instrumented with strainmeters, tiltmeters, and seismometers, in collaboration with a Japanese team led by former DTM predoctoral fellow Kiyoshi Suyehiro. One hole is about 15 km above an area of active seismicity, which illuminates the subduction interface. The other is in a similar position, but the interface is seismically quiet. Since the plate motion here is about 10 cm per year, there is a strong expectation that these data will soon provide new insight into the complex behavior of this important subduction zone.

Observing Transient Deformation

PAUL G. SILVER

Transient deformation in the Earth's crust is one of the important sources of information about the processes that trigger seismic events. In collaboration with postdoctoral fellow Stephen Gao and Staff Members Alan Linde and Selwyn Sacks, I have been examining two very interesting transients that may shed light on the earthquake-triggering process.

As discussed at greater length above by Selwyn Sacks, it is not unusual to observe slow multiyear deformation following a large earthquake, as the crust slowly adjusts to the change in the stress field brought about by such an event. It is much more unusual to observe such slow deformation unrelated to a large earthquake. We have observed one such event, and it produced an increase in the slip velocity along the San Andreas Fault that began in 1993 and continues to the present. This transient was observed in the Parkfield region of central California—a site of an expected magnitude 6 earthquake. This expectation is based on a past sequence of earthquakes that ruptured the same patch of the fault every 22 years on average. While the anticipated Parkfield earthquake has not yet occurred, the resulting concentration of many different kinds of strain instrumentation has produced an unprecedented data set spanning 15 years of observations. The instrumentation used includes two-color electronic distance meters (EDMs), which are similar in precision to the better-known GPS receivers; creepmeters, which measure motion locally across the fault; borehole strainmeters, including those produced at DTM; and borehole seismometers for detecting microearthquake activity, which is a useful measure of strain in the seismogenic zone beneath the surface. The integration of data from all these instruments reveals a fascinating deformation event.

The most easily observable aspect of the transient, from the EDM and creep data, shows a speeding up of the San Andreas Fault slip from 1 cm/yr to 1.3 cm/yr beginning in 1993. The increase in slip rate corresponds temporally to a dramatic increase in general seismic activity, including the occurrence of four M ~ 4 earthquakes that occurred along a 6-km segment of the fault just northwest of the EDM network. There was also a synchronous change in borehole shear strain rate. Such a change in slip and strain rate requires that the conditions on the fault have changed: either the resistance to slip on the fault has been reduced, or the stress driving the fault slip has increased.

Modeling of the EDM and borehole strain data provides a means for distinguishing between these two possibilities. Indeed, the data suggest that the stress has increased as a result of even larger slow aseismic slip to the north that loaded the southern segment. This larger event was probably triggered by the occurrence of the four seismic events. The existence of this northern slip transient is not directly visible from surface observations, but it has been inferred from careful analysis of the rate of microearthquake activity. Thus, the examination of these various sources of data reveals a complex

episode of transient deformation and stress redistribution. Such events have only occasionally been observed, and we presently know relatively little about them. They nevertheless represent a phenomenon that could significantly increase our understanding of the redistribution of stress and strain in the crust and its relation to the occurrence of earthquakes.

Another intriguing transient involves the M_w = 7.3 Landers earthquake of June 28, 1992. Since the occurrence of this earthquake, there has been heightened interest in the topic of triggered seismicity, because this event was followed by intense seismic activity for several weeks over a broad area encompassing much of the western United States. To see if there was a long-term effect, we examined all earthquakes, including the very smallest. We found that the short-term triggering was only the beginning of a previously unrecognized longer-term (five-year) trend, consisting of a persistently elevated, but decaying, microearthquake rate (Fig. 13). This finding suggests that the changes brought about by this earthquake were both widespread and semipermanent, essentially sensitizing a large area to small stress perturbations.

Perhaps even more surprising, this seismicity excess was modulated by an annual cycle, in which there was a maximum of earthquakes in the fall and a minimum in the spring (Fig. 13). Much of this signal comes from volcanic/ hydrothermal areas (Fig. 14) where the short-term triggering was clearly observed. There are several possible environmental sources of stress that might give rise to this cycle, including tidal loading, precipitation, and barometric pressure. For a variety of reasons, barometric pressure appears to be the most plausible of the three. Whichever is in fact the cause, it implies that very small environmental stresses of order tens of millibars are capable of triggering small seismic events.

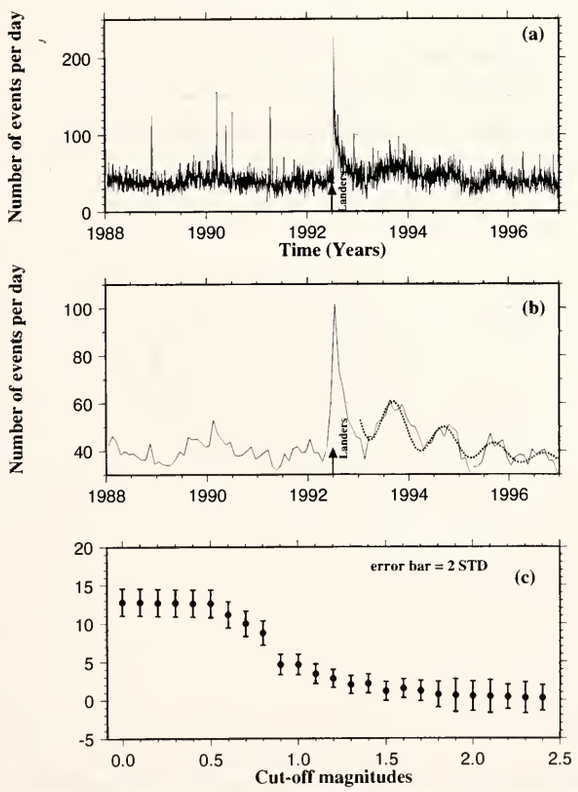


Fig. 13. A time series of seismicity rate (events/day) and amplitude of the annual cycle is shown here: (a) number of events per day; (b) monthly average of number of events per day (solid line), fit to a decaying sinusoid with an annual period (dotted line); (c) amplitude of the annual cycle (and uncertainty) calculated using different cutoff magnitudes. The amplitude is significantly different from zero for events less than magnitude 1.7.

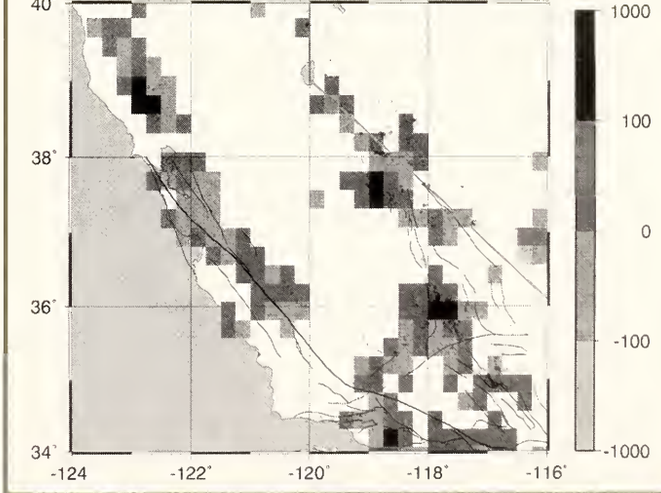


Fig. 14. This map shows the spatial distribution of the annual cycle (defined as the difference in the total number of events between the second half and the first half of the year) for the post-Landers period. Dark areas (at lat 39°, long -123°; lat 37°, long -119°; and lat 36°, long -118°) show the largest annual cycle, with more events in the fall than in the spring. Dots denote events that occurred within 10 days after Landers and reflect regions of short-term triggering. Note that the annual cycle is seen where there was short-term triggering.

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Extradepartmental and Administrative

Carnegie Administrative Personnel

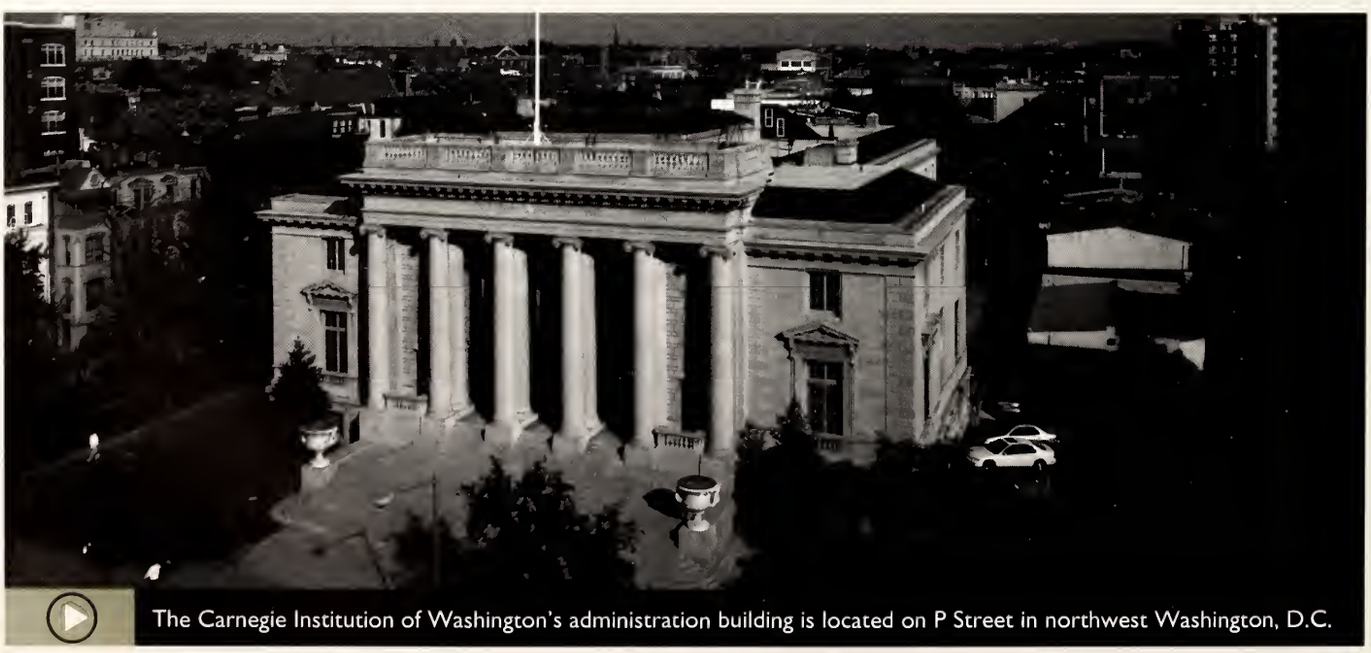
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Gloria Brienza, *Budget and Management Analysis Manager*
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Catherine Whittenburg, *Assistant Editor*[10]
Jacqueline Williams, *Assistant to Manager/Human Resources and Insurance*

[1] From October 15, 1998
[2] To January 31, 1999
[3] To January 29, 1999
[4] To June 15, 1999
[5] From October 2, 1998
[6] From July 20, 1998
[7] From January 4, 1999
[8] From February 1, 1999
[9] To April 30, 1999
[10] To September 25, 1998

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[1] Summer Institute, 1998
[2] Summer Institute, 1999



The Carnegie Institution of Washington's administration building is located on P Street in northwest Washington, D.C.



On May 5, 1999, Carnegie President Maxine Singer was recognized for her lifetime of achievements. M.R.C. Greenwood, Chancellor of the University of California, Santa Cruz, presented Dr. Singer with the prestigious Vannevar Bush Award from the National Science Board of the National Science Foundation. The award is the highest honor bestowed by the board and Dr. Singer is the first woman ever to receive it.

Publications of the President

Berg, P., and M. F. Singer, Inspired choices, *Science 282*, 873, 1998.

Berg, P., and M. F. Singer, Regulating human cloning, *Science 282*, 413, 1998.

Singer, M. F., Believing Is Not Understanding, *Washington Post*, OpEd page, August 18, 1999.

The Capital Science Lectures are sponsored by the institution with substantial support from Baxter International Inc., the Bell Atlantic Foundation, Human Genome Sciences, Inc., and the Johnson & Johnson Family of Companies. The lectures—free and open to the public—are held in the Root Auditorium at Carnegie's headquarters at 16th and P Streets in northwest Washington, D. C. Speakers also meet informally with groups of high school students. During the 1998-1999 year, the following lectures were given:

CAPITAL SCIENCE LECTURES

Prion Biology and Diseases, by Stanley B. Prusiner (Department of Neurology, University of California, San Francisco), October 13, 1998

Return to the Center of the Universe: Our Search for Place and Purpose, by Alan Dressler (The Observatories of the Carnegie Institution of Washington), November 17, 1998

The Early Evolution of Animals, by Andrew H. Knoll (Department of Organismic and Evolutionary Biology, Harvard University), December 15, 1998

Planetary Perspectives on Life in the Solar System, by Christopher F. Chyba (The SETI Institute and Department of Geological and Environmental Studies, Stanford University), January 26, 1999

Volcanic Eruptions: Watching the Magma Rise from Depth, by Alan Linde (Department of Terrestrial Magnetism, Carnegie Institution of Washington), February 23, 1999

Too Much of a Good Thing? Fertilizer and Global Change in the Nitrogen Cycle, by Pamela A. Matson (Department of Geological and Environmental Sciences and the Institute of International Studies, Stanford University), March 23, 1999

Cancer Development and Cell Immortality, by Robert A. Weinberg (Whitehead Institute for Biomedical Research, Massachusetts Institute of Technology), April 20, 1999

Phytochemicals: Plant Sex, Human Drugs, and Insect Rock and Roll, by May Berenbaum (Department of Entomology, University of Illinois at Urbana-Champaign), May 18, 1999

Financial Statements
for the year ended June 30, 1999

Financial Profile

Reader's Note: Reader's Note: In this section, any discussion of spending levels or endowment amounts are on a cash or cash-equivalent basis. Therefore, the funding amounts presented do not reflect the impact of capitalization, depreciation, or other non-cash amounts.

The primary source of support for Carnegie Institution of Washington's activities is its endowment. This reliance has led to an important degree of independence in the research program of the Institution. This independence is anticipated to continue as a mainstay of Carnegie's approach to science in the future.

At June 30, 1999, the endowment was valued at approximately $451.6 million. For a number of years, Carnegie's endowment has been allocated among a broad spectrum of asset classes. This includes fixed-income instruments (bonds), equities (stocks), absolute return investments, real estate partnerships, private equity, an oil and gas partnership and a hedge fund. The Finance Committee of the Board regularly examines the asset allocation of the endowment and readjusts the allocation, as appropriate. The Institution relies upon external managers and partnerships to conduct these investment activities, and it employs a commercial bank to maintain custody.

The goal of diversifying the endowment into alternative assets is to reduce the volatility inherent in an undiversified portfolio while generating attractive overall performance.

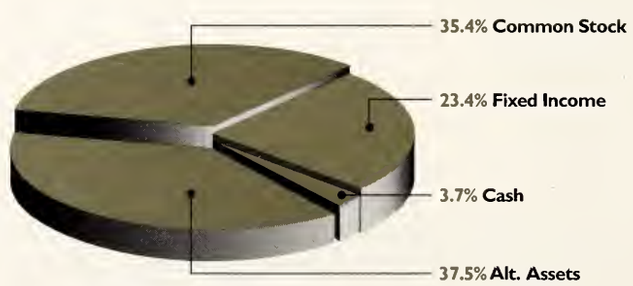
In its private equity allocation, the Institution accepts a higher level of risk in exchange for a higher return. By entering into real estate partnerships, the Institution in effect, holds part of its endowment in high-quality commercial real estate, deriving both capital appreciation and income in the form of rent from tenants. Along with the oil and gas partnership, this asset class provides an effective hedge against inflation. Finally, through its investments in an absolute return partnership and a hedge fund, the Institution seeks to achieve long-term returns similar to those of traditional U.S. equities with reduced volatility and risk.

For the fiscal year ended on June 30, 1999, Carnegie's endowment had a total return (net of management fees) of 11.6%. The annualized five-year return for the endowment was 15.1%.

The following chart shows the allocation of the Institution's endowment among the asset classes it uses as of June 30, 1999:

	Target Allocation	Actual Allocation
Common Stock	35%	35.4%
Alternative Assets	40%	37.5%
Fixed Income	25%	23.4%
Cash	0%	3.7%

Actual Asset Allocation



Endowment Spending Over Seven Years

(Dollars in Millions)

FY	92-93	93-94	94-95	95-96	96-97	97-98	98-99
Endowment Spending	$12.5	$12.4	$13.9	$15.1	$15.5	$16.4	$20.9
Actual Market Value at June 30	$270.4	$275.5	$304.5	$338.0	$382.9	$423.3	$451.6
Actual Spending as % of Market Value	4.63%	4.51%	4.57%	4.48%	4.05%	3.87%	4.63%
Planned Spending Rate in Budget	5.86%	5.81%	5.76%	5.71%	5.66%	5.61%	5.50%

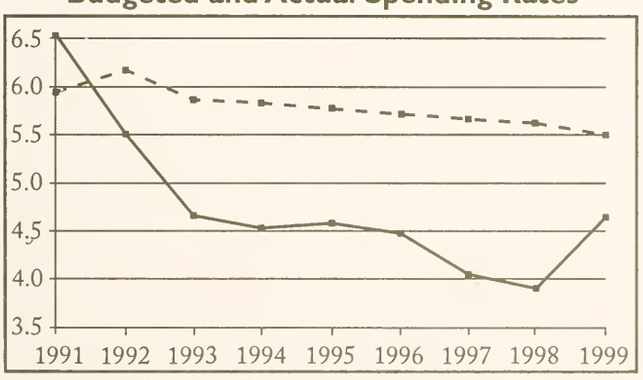
Carnegie's primary purpose is to maintain the long-term spending power of its endowment. To achieve this objective, it employs a budgeting methodology that provides for:

- averaging the total market value of the endowment for the three most recent fiscal years, and
- developing a budget that spends at a set percentage (spending rate) of this three-year market average.

During the 1990s, this budgeted spending rate has been declining in a phased reduction, moving towards an informal goal of an actual, average spending rate of 4.5%. For the 1998-1999 fiscal year, the rate was budgeted at 5.5%. While Carnegie has been reducing this budgeted rate by between 5 and 10 basis points a year, there has also been continuing, significant growth in the size of the endowment. The result has been that, for the 1998-1999 fiscal year, the actual spending rate (the ratio of annual spending from the endowment to actual endowment value at the conclusion of the fiscal year in which the spending took place) was 4.63%.

The table below left compares the planned versus the actual spending rates, as well as the market value of the endowment from 1991-1992 to the most recently concluded fiscal year, 1998-1999.

Budgeted and Actual Spending Rates



Within Carnegie's endowment, there are a number of "Funds" that provide support either in a general way or in a targeted way, with a specific, defined purpose. The largest of these is the Andrew Carnegie Fund, begun with the original gift of $10 million. Mr. Carnegie later made additional gifts totaling another $12 million during his lifetime. This fund is now valued at nearly $376 million.

UNAUDITED

The following table shows the amounts in the principal funds within the institution's endowment as of June 30, 1999:

Market value of the Principal Funds Within Carnegie's Endowment

Andrew Carnegie	$375,976,205
Capital Campaign	28,828,808
Mellon Matching	9,595,334
Anonymous	8,019,950
Astronomy Funds	7,490,092
Anonymous Matching	7,295,719
Wood	4,936,744
Carnegie Futures	3,234,707
Golden	3,028,396
Bowen	2,312,677
Science Education Fund	1,956,744
Colburn	1,907,247
McClintock Fund	1,497,552
Special Instrumentation	1,035,100
Bush Bequest	931,004
Moseley Astronomy	763,580
Starr Fellowship	723,253
Special Opportunities	687,603
Roberts	400,437
Lundmard	315,281
Morgenroth	232,288
Hollaender	222,507
Moseley	138,397
Forbush	131,085
Bush	110,700
Green Fellowship	97,244
Harkavy	88,744
Hale	88,206
Total	$462,045,604

Financial Statements and Schedule

Independent Auditors' Report

To the Auditing Committee of the Carnegie Institution of Washington:

We have audited the accompanying statements of financial position of the Carnegie Institution of Washington (Carnegie) as of June 30, 1999 and 1998, and the related statements of activities and cash flows for the years then ended. These financial statements are the responsibility of Carnegie's management. Our responsibility is to express an opinion on these financial statements based on our audits.

We conducted our audits in accordance with generally accepted auditing standards. Those standards require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements. An audit also includes assessing the accounting principles used and significant estimates made by management, as well as evaluating the overall financial statement presentation. We believe that our audits provide a reasonable basis for our opinion.

In our opinion, the financial statements referred to above present fairly, in all material respects, the financial position of the Carnegie Institution of Washington as of June 30, 1999 and 1998, and its changes in net assets and its cash flows for the years then ended, in conformity with generally accepted accounting principles.

Our audits were made for the purpose of forming an opinion on the basic financial statements taken as a whole. The supplementary information included in Schedule 1 is presented for purposes of additional analysis and is not a required part of the basic financial statements. Such information has been subjected to the auditing procedures applied in the audits of the basic financial statements and, in our opinion, is fairly presented in all material respects in relation to the basic financial statements taken as a whole.

KPMG LLP

Washington, D.C.
October 29, 1999

Statements of Financial Position

June 30, 1999 and 1998

Assets	1999	1998
Cash and cash equivalents	$ 247,697	147,343
Accrued investment income	537,470	665,437
Contributions receivable (note 2)	2,119,791	2,414,271
Accounts receivable and other assets	4,096,520	2,573,029
Bond proceeds held by trustee (note 6)	1,665,390	7,162,230
Investments (note 3)	462,045,604	431,802,740
Construction in progress (notes 4 and 5)	54,056,641	40,642,497
Property and equipment, net (note 4)	45,333,399	41,607,411
	$ 570,102,512	**527,014,958**
Liabilities and Net Assets		
Accounts payable and accrued expenses	$ 2,896,622	2,409,330
Deferred revenue (note 5)	25,476,955	12,108,046
Broker payable (note 3)	—	2,171,665
Bonds payable (note 6)	34,843,325	34,806,460
Accrued postretirement benefits (note 7)	9,968,543	9,836,437
Total liabilities	73,185,445	61,331,938
Net assets (note 8):		
Unrestricted:		
Board designated:		
Invested in fixed assets, net	39,069,760	35,335,402
Designated for managed investments	401,014,333	369,733,863
Undesignated	5,190,932	10,489,238
	445,275,025	415,558,503
Temporarily restricted	14,002,694	14,172,427
Permanently restricted	37,639,348	35,952,090
Total net assets	496,917,067	465,683,020
Commitments and contingencies (notes 9, 10, and 11)		
Total liabilities and net assets	**$ 570,102,512**	**527,014,958**

See accompanying notes to financial statements.

Statements of Activities

Years ended June 30, 1999 and 1998

	1999				1998			
	Unrestricted	Temporarily restricted	Permanently restricted	Total	Unrestricted	Temporarily restricted	Permanently restricted	Total
Revenues and support:								
Grants and contracts	$ 12,013,129	—	—	12,013,129	11,259,930	—	—	11,259,930
Contributions and gifts	77,801	3,916,380	1,630,265	5,624,446	709,030	3,894,584	1,144,309	5,747,923
Net gain (loss) on disposals of property	60,558	—	—	60,558	(90,224)	—	—	(90,224)
Other income	1,188,846	—	—	1,188,846	720,656	—	—	720,656
Net external revenue	13,340,334	3,916,380	1,630,265	18,886,979	12,599,392	3,894,584	1,144,309	17,638,285
Investment income (note 3)	45,210,087	2,027,818	56,993	47,294,898	54,982,546	4,016,507	124,973	59,124,026
Net assets released from restrictions (note 8)	6,113,931	(6,113,931)	—	—	9,324,754	(9,324,754)	—	—
Total revenues, gains, and other support	64,664,352	(169,733)	1,687,258	66,181,877	76,906,692	(1,413,663)	1,269,282	76,762,311
Program and supporting services expenses:								
Terrestrial Magnetism	6,576,909	—	—	6,576,909	6,221,701	—	—	6,221,701
Observatories	6,687,508	—	—	6,687,508	5,799,559	—	—	5,799,559
Geophysical Laboratory	6,868,289	—	—	6,868,289	6,283,859	—	—	6,283,859
Embryology	5,567,359	—	—	5,567,359	5,163,256	—	—	5,163,256
Plant Biology	4,840,611	—	—	4,840,611	4,562,436	—	—	4,562,436
Other Programs	1,005,455	—	—	1,005,455	1,050,946	—	—	1,050,946
Administrative and general expenses	3,401,699	—	—	3,401,699	2,316,114	—	—	2,316,114
Total expenses	34,947,830	—	—	34,947,830	31,397,871	—	—	31,397,871
Increase (decrease) in net assets	29,716,522	(169,733)	1,687,258	31,234,047	45,508,821	(1,413,663)	1,269,282	45,364,440
Net assets at the beginning of the year	415,558,503	14,172,427	35,952,090	465,683,020	370,049,682	15,586,090	34,682,808	420,318,580
Net assets at the end of the year	$ 445,275,025	14,002,694	37,639,348	496,917,067	415,558,503	14,172,427	35,952,090	465,683,020

See accompanying notes to financial statements.

Statements of Cash Flows

Years ended June 30, 1999 and 1998

	1999	1998
Cash flows from operating activities:		
Increase in net assets	$ 31,234,047	45,364,440
Adjustments to reconcile increase in net assets to net cash provided by operating activities:		
Depreciation	2,902,842	2,488,284
Net gains on investments	(37,191,987)	(47,591,512)
Loss (gain) on disposal of property	(60,558)	90,224
Amortization of bond issuance costs and discount	36,865	36,865
Contribution of stock	(543,136)	(1,425,784)
(Increase) decrease in assets:		
Receivables	(1,229,011)	793,664
Accrued investment income	127,967	(169,530)
Increase in liabilities:		
Accounts payable and accrued expenses	487,292	341,236
Deferred revenues	13,368,909	10,958,996
Accrued postretirement benefits	132,106	599,454
Contributions and investment income restricted for long-term investment	(4,350,629)	(2,716,782)
Net cash provided by (used for) operating activities	4,914,707	8,769,555
Cash flows from investing activities:		
Draws from bond proceeds held by trustee	5,496,840	3,997,646
Acquisition of property and equipment	(6,568,272)	(6,305,806)
Construction of telescope, facilities, and equipment	(13,414,144)	(11,905,053)
Investments purchased, net of change in broker payable of $0 and ($2,171,665) in 1999 and 1998, respectively	(474,633,607)	(427,075,566)
Proceeds from investments sold or matured	479,954,201	427,190,728
Net cash (used for) provided by investing activities	(9,164,982)	(14,098,051)
Cash flows from financing activities – proceeds from contributions and investment income restricted for:		
Investment in endowment	1,630,265	1,269,282
Investment in property and equipment	2,720,364	1,447,500
Net cash provided by financing activities	4,350,629	2,716,782
Net increase (decrease) in cash and cash equivalents	100,354	(2,611,714)
Cash and cash equivalents at the beginning of the year	147,343	2,759,057
Cash and cash equivalents at the end of the year	**$ 247,697**	**147,343**
Supplementary cash flow information		
Cash paid for interest	**$ 1,488,410**	**1,568,792**

See accompanying notes to financial statements.

Notes to Financial Statements

June 30, 1999 and 1998

(1) Organization and Summary of Significant Accounting Policies

Organization

The Carnegie Institution of Washington (Carnegie) conducts advanced research and training in the sciences. It carries out its scientific work in five research centers located throughout the United States and at an observatory in Chile. The centers are the Departments of Embryology, Plant Biology, and Terrestrial Magnetism, the Geophysical Laboratory, and the Observatories (astronomy). Income from investments represents approximately 75 percent of Carnegie's total revenues. Carnegie's external income is mainly from gifts and federal grants and contracts.

Basis of Accounting and Presentation

The financial statements are prepared on the accrual basis of accounting. Contributions and gifts revenues are classified according to the existence or absence of donor-imposed restrictions. Also, satisfaction of donor-imposed restrictions are reported as releases of restrictions in the statements of activities.

Investments and Cash Equivalents

Carnegie's debt and equity investments are reported at their fair values. Carnegie also reports investments in partnerships at fair value as determined and reported by the general partners. All changes in fair value are recognized in the statements of activities. Carnegie considers all highly liquid debt instruments purchased with remaining maturities of 90 days or less to be cash equivalents. Money market and other highly liquid instruments held by investment managers are reported as investments.

Income Taxes

Carnegie is exempt from federal income tax under Section 501(c)(3) of the Internal Revenue Code (the Code). Accordingly, no provision for income taxes is reflected in the accompanying financial statements. Carnegie is also an educational institution within the meaning of Section 170(b)(1)(A)(ii) of the Code. The Internal Revenue Service has classified Carnegie as other than a private foundation, as defined in Section 509(a) of the Code.

Fair Value of Financial Instruments

Financial instruments of Carnegie include cash equivalents, receivables, investments, bond proceeds held by trustee, accounts and broker payables, and bonds payable. The fair value of investments in debt and equity securities is based on quoted market prices. The fair value of investments in limited partnerships is based on information provided by the general partners.

The fair value of Series A bonds payable is based on quoted market prices. The fair value of Series B bonds payable is estimated to be the carrying value, since these bonds bear adjustable market rates.

The fair values of cash equivalents, receivables, and accounts and broker payables approximate their carrying values based on their short maturities.

Use of Estimates

The preparation of financial statements in conformity with generally accepted accounting principles requires management to make estimates and assumptions that affect the reported amounts of assets and liabilities and disclosure of contingent assets and liabilities at the date of the financial statements. They also affect the reported amounts of revenues and expenses during the reporting period. Actual results could differ from those estimates.

Property and Equipment

Carnegie capitalizes expenditures for land, buildings and leasehold improvements, telescopes, scientific and administrative equipment, and projects in progress. Routine replacement, maintenance, and repairs are charged to expense.

Depreciation is computed on a straight-line basis over the following estimated useful lives:

Buildings and telescopes	50 years
Leasehold improvements	lesser of 25 years or the remaining term of the lease
Scientific and administrative equipment	5 years

Contributions

Contributions are classified based on the existence or absence of donor-imposed restrictions. Contributions and net assets are classified as follows:

Unrestricted – includes all contributions received without donor-imposed restrictions on use or time.

Temporarily restricted – includes contributions with donor-imposed restrictions as to purpose of gift or time period expended.

Permanently restricted – generally includes endowment gifts in which donors stipulated that the corpus be invested in perpetuity. Only the investment income generated from endowments may be spent. Certain endowments require that a portion of the investment income be reinvested in perpetuity.

Gifts of long-lived assets, such as buildings or equipment, are considered unrestricted when placed in service. Cash gifts restricted for investment in long-lived assets are released from restriction when the asset is acquired or as costs are incurred for asset construction.

Grants

Carnegie records revenues on grants from federal agencies only to the extent that reimbursable expenses are incurred. Accordingly, funds received in excess of reimbursable expenses are recorded as deferred revenue, and expenses in excess of reimbursements are recorded as accounts receivable. Reimbursement of indirect costs is based upon provisional rates which are subject to subsequent audit by Carnegie's federal cognizant agency, the National Science Foundation.

Allocation of Costs

The costs of providing programs and supporting services have been summarized in the statements of activities. Accordingly, certain costs have been allocated among the programs and supporting services benefited.

Reclassifications

Certain prior year amounts were reclassified to conform to the current year presentation.

(2) Contributions Receivable

Contributions receivable representing unconditional promises expected to be collected are summarized as follows at June 30, 1999 and 1998:

Years ending June 30,	1999	1998
2000	$ 825,100	2,041,690
2001	665,000	144,690
2002	400,000	102,000
2003	14,938	71,891
2004	10,000	27,000
2005 and later	204,753	27,000
	$2,119,791	**2,414,271**

(3) Investments

At June 30, 1999 and 1998, investments at fair value consisted of the following:

	1999	1998
Time deposits and money market funds	$ 129,474,938	20,253,740
Debt mutual funds	4,707,631	55,886,196
Debt securities	8,385,121	40,071,660
Equity securities	149,946,198	155,190,157
Real estate partnerships	53,058,884	51,744,690
Limited partnerships	116,472,832	108,656,297
	$ 462,045,604	**431,802,740**

Investment income for the years ended June 30, 1999 and 1998, consisted of the following:

	1999	1998
Interest and dividends	$ 11,484,577	13,092,269
Net realized gains	24,124,433	28,100,705
Net unrealized gains	13,067,554	19,490,807
Less – investment management expenses	(1,381,666)	(1,559,756)
	$ 47,294,898	**59,124,025**

Carnegie purchased and sold certain investment securities on dates prior to June 30, 1998. These trades were settled subsequent to June 30, 1998, and are reflected in the investment balances reported at year end. The net obligation for these unsettled trades is reported as broker payable in the accompanying statements of financial position.

As of June 30, 1999, the fair value for approximately $43 million of Carnegie's $170 million of real estate and limited partnership investments has been estimated by the general partners in the absence of readily ascertainable market values. However, these estimated fair values may differ from the values that would have been used had a ready market existed.

(4) Property and Equipment

At June 30, 1999 and 1998, property and equipment placed in service consisted of the following:

	1999	1998
Buildings and improvements	$ 43,569,957	38,904,093
Scientific equipment	17,379,687	15,917,470
Telescopes	7,910,825	7,910,825
Administrative equipment	2,507,290	2,334,975
Land	787,896	787,896
Art	34,067	34,067
	72,189,722	65,889,326
Less accumulated depreciation	26,856,323	24,281,915
	$ 45,333,399	**41,607,411**

At June 30, 1999 and 1998, construction in progress consisted of the following:

	1999	1998
Telescope	$50,731,430	38,447,209
Buildings	802,523	1,147,369
Scientific equipment	2,522,688	1,047,919
	$54,056,641	**40,642,497**

At June 30, 1999 and 1998, approximately $59 million and $44 million, respectively, of construction in progress and other property, net of accumulated depreciation, was located in Las Campanas, Chile. During 1999 and 1998, Carnegie capitalized interest costs (net of interest earned of $245,000 and $489,000, respectively) of approximately $1,229,000 and $1,118,000, respectively, as construction in progress.

(5) Magellan Consortium

During the year ended June 30, 1998, Carnegie entered into an agreement (Magellan Agreement) with four universities establishing a consortium to build and operate the Magellan telescopes. The two Magellan telescopes are currently under construction on Manqui Peak, Las Campanas in Chile. The total construction costs of the two telescopes is expected to be approximately $72 million and will be recorded as assets by Carnegie. Title to the Magellan facilities is held by Carnegie. As of June 30, 1999, construction in progress of $50,731,430 related to the Magellan project.

The university members of the consortium, by contribution to the construction and operating costs of Magellan, acquire rights of access and oversight as described in the Magellan Agreement. Total contributions by the university members for construction are expected to be $36 million, 50% of the total expected costs and these monies are being used by Carnegie to finance part of the Magellan Telescopes' construction costs. As of June 30, 1999, the university members had contributed $24,910,264 which is included in deferred revenue in the accompanying statements of financial position. The deferred revenue will be recognized ratably as income over the estimated useful lives of the telescopes.

(6) Bonds Payable

On November 1, 1993, Carnegie issued $17.5 million each of secured Series A and Series B California Educational Facilities Authority Revenue tax-exempt bonds. Bond proceeds are used to finance the Magellan telescope project and the renovation of the facilities of the Observatories at Pasadena. The balances outstanding at June 30, 1999 and 1998, on the Series A issue totaled $17,402,913 and $17,380,068, respectively, and on the Series B issue totaled $17,440,413 and $17,426,392, respectively. The balances outstanding are net of unamortized bond issue costs and bond discount. Bond proceeds held by the trustee and unexpended at June 30, 1999 and 1998, totaled $1,665,390 and $7,162,230, respectively.

Series A bonds bear interest at 5.6 percent payable in arrears semiannually on each April 1 and October 1 and upon maturity on October 1, 2023. Series B bonds bear interest at variable money market rates (ranging from 2.8% to 3.2% at June 30, 1999) in effect from time to time, up to a maximum of 12 percent over the applicable money market rate period of between one and 270 days and have a stated maturity of October 1, 2023. At the end of each money market rate period, Series B bondholders are required to offer the bonds for repurchase at the applicable money market rate. If repurchased, the Series B bonds would be resold at the current applicable money market rate and for a new rate period.

Carnegie is not required to repay the Series A and B bonds until the October 1, 2023, maturity date, and Carnegie has the intent and the ability to effect the purchase and resale of the Series B bonds through a tender agent; therefore all bonds payable are classified as long term. Sinking fund redemptions begin in 2019 in installments for both series. The fair value of Series A bonds payable at June 30, 1999 and 1998, based on quoted market prices is estimated at $18,043,000 and $18,600,000, respectively. The fair value of Series B bonds payable at June 30, 1999 and 1998, is estimated to approximate carrying value as the mandatory tender dates on which the bonds are repriced are generally within three months of year end.

(7) Employee Benefit Plans

Retirement Plan

Carnegie has a noncontributory, defined contribution, money-purchase retirement plan in which all United States personnel are eligible to participate. After one year's participation, an individual's benefits are fully vested. The Plan has been funded through individually owned annuities issued by Teachers' Insurance and Annuity Association (TIAA) and College Retirement Equities Fund (CREF). Total contributions made by Carnegie totaled approximately $2,133,000 and $1,851,000 for the years ended June 30, 1999 and 1998, respectively.

Postretirement Benefits Plan

Carnegie provides postretirement medical benefits to all employees who retire after age 55 and have at least ten years of service. Cash payments made by Carnegie for these benefits totaled approximately $318,000 and $341,000 for the years ended June 30, 1999 and 1998, respectively.

The expense for postretirement benefits for the years ended June 30, 1999 and 1998 consists of the following:

	1999	1998
Service cost – benefits earned during the year	$283,000	237,000
Interest cost on projected benefit obligation	531,000	502,000
Amortization of gain	(45,000)	(112,000)
Accrued postretirement benefit cost	**$769,000**	**627,000**

The 1999 postretirement benefits expense was approximately $451,000 more than the cash expense of $318,000, and the 1998 postretirement benefits expense was approximately $286,000 more than the cash expense of $341,000. The postretirement benefits expense was allocated among program and supporting services expenses in the statements of activities.

The reconciliation of the Plan's funded status to amounts recognized in the financial statements at June 30, 1999 and 1998 follows:

	1999	1998
Change in benefit obligation:		
Benefit obligation at beginning of year	$ 8,041,000	9,237,000
Service cost	283,000	237,000
Interest cost	531,000	502,000
Actuarial gain	(689,000)	(1,594,000)
Benefits paid	(318,000)	(341,000)
Benefit obligation at end of year	7,848,000	8,041,000
Change in plan assets:		
Fair value of plan assets at beginning of year	—	—
Actual return on plan assets	—	—
Contribution to plan	318,000	341,000
Benefits paid	(318,000)	(341,000)
Fair value of plan assets at end of year	—	—
Funded status	(7,848,000)	(8,041,000)
Unrecognized net actuarial gain	(2,120,000)	(1,795,000)
Prepaid (accrued) benefit cost	**$(9,968,000)**	**(9,836,000)**

The present value of the benefit obligation as of June 30, 1999, was determined using an assumed health care cost trend rate of 9.0 percent and an assumed discount rate of 7.5 percent. The present value of the benefit obligation as of June 30, 1998, was determined using an assumed health care cost trend rate of 9.4 percent and an assumed discount rate of 6.75 percent. Carnegie's policy is to fund postretirement benefits as claims and administrative fees are paid.

For measurement purposes, a 9.0 percent annual rate of increase in the per capita cost of covered health care benefits was assumed for 1999; the rate was assumed to decrease gradually to 5.5 percent in 12 years and remain at that level thereafter. The health care cost trend rate assumption has a significant effect on the amounts reported. A one-percentage change in assumed annual health care cost trend rate would have the following effects:

	One-percentage point increase	One-percentage point decrease
Effect on total of service and interest Cost components	$165,000	(140,000)
Effect on postretirement benefit obligation	1,023,000	(837,000)

(8) Net Assets

At June 30, 1999 and 1998, temporarily restricted net assets were available to support the following donor-restricted purposes:

	1999	1998
Specific research programs	$10,479,226	9,278,140
Equipment acquisition and construction	3,523,468	4,894,287
	$14,002,694	**14,172,427**

At June 30, 1999 and 1998, permanently restricted net assets consisted of permanent endowments, the income from which is available to support the following donor-restricted purposes:

	1999	1998
Specific research programs	$14,434,629	12,747,371
Equipment acquisition and construction	1,204,719	1,204,719
General support (Carnegie endowment)	22,000,000	22,000,000
	$37,639,348	**35,952,090**

During 1999 and 1998, Carnegie met donor-imposed requirements on certain gifts and, therefore, released temporarily restricted net assets as follows:

	1999	1998
Specific research programs	$2,022,748	3,979,778
Equipment acquisition and construction	4,091,183	5,344,976
	$6,113,931	**9,324,754**

(9) Federal Grants and Contracts

Costs charged to the federal government under cost-reimbursement grants and contracts are subject to government audit. Therefore, all such costs are subject to adjustment. Management believes that adjustments, if any, would not have a significant effect on the financial statements.

(10) Commitments

In 1997, Carnegie entered into a contract with the University of Arizona for the construction of the primary mirror and support system for the second telescope in the Magellan project. The amount of the contract is approximately $9,700,000 of which approximately $3,646,000 had not been incurred at June 30, 1999. Carnegie had previously entered into an agreement with the University of Arizona for the primary mirror and support system for the first telescope and had outstanding commitments of approximately $63,490 at June 30, 1999. Carnegie also has other contracts relating to the construction of Magellan with outstanding commitments totaling approximately $3,758,547.

Carnegie has outstanding commitments to invest approximately $25 million in limited partnerships.

(11) Lease Arrangements

Carnegie leases a portion of the land it owns in Las Campanas, Chile to other organizations. These organizations have built and operate telescopes on the land. Most of the lease arrangements are not specific and some are at no-cost to the other organizations. One of the lease arrangements is noncancelable and has annual future rents of $120,000 through fiscal year 2001. For the no-cost leases, the value of the leases could not be determined and is not considered significant, and, accordingly, contributions have not been recorded in the financial statements.

Carnegie also leases a portion of one of its laboratories to another organization for an indefinite term. Rents to be received under the agreement are approximately $339,000 annually, adjusted for CPI increases.

Carnegie leases land and buildings. The monetary terms of the leases are considerably below fair value, however, these terms were developed considering other non-monetary transactions between Carnegie and the lessors. The substance of the transactions indicates arms-length terms between Carnegie and the lessors. The monetary value of the leases could not be determined, and has not been recorded in the financial statements.

(12) Year 2000

Carnegie is in the process of addressing anticipated operational issues resulting from the Year 2000. The Year 2000 problem is typically the result of computer programs using two digits rather than four digits to define the applicable year for date interpretation. Management believes that mission-critical systems will be functioning as necessary to avoid any major business interruption. However, no assurance can be given that Carnegie can or will become Year 2000 compliant.

Schedules of Expenses

Schedule 1

Years ended June 30, 1999 and 1998

	1999			1998		
	Carnegie funds	Federal and private grants	Total expenses	Carnegie funds	Federal and private grants	Total expenses
Personnel costs:						
Salaries	$ 11,268,614	3,171,189	14,439,803	10,341,061	2,852,217	13,193,278
Fringe benefits and payroll taxes	3,975,980	869,052	4,845,032	3,512,361	773,285	4,285,646
Total personnel costs	15,244,594	4,040,241	19,284,835	13,853,422	3,625,502	17,478,924
Fellowship grants and awards	1,319,122	983,363	2,302,485	1,325,949	888,367	2,214,316
Depreciation	2,902,842	—	2,902,842	2,474,898	—	2,474,898
General expenses:						
Educational and research supplies	988,536	1,365,473	2,354,009	866,150	1,000,382	1,866,532
Building maintenance and operation	2,315,995	57,701	2,373,696	1,512,049	33,229	1,545,278
Travel and meetings	690,237	530,656	1,220,893	634,442	530,816	1,165,258
Publications	33,249	57,932	91,181	38,197	84,898	123,095
Shop	57,705	—	57,705	57,282	—	57,282
Telephone	199,023	10,438	209,461	175,120	12,613	187,733
Books and subscriptions	264,491	7,430	271,921	226,358	9,328	235,686
Administrative and general	683,797	163,110	846,907	647,577	161,494	809,071
Printing and copying	148,385	8,465	156,850	91,256	2,546	93,802
Shipping and postage	134,230	36,591	170,821	110,560	65,522	176,082
Insurance, taxes and professional fees	740,853	164,278	905,131	663,824	138,847	802,671
Equipment	—	1,432,203	1,432,203	—	1,914,681	1,914,681
Fund-raising expense	366,890	—	366,890	321,420	—	321,420
Total general expenses	6,623,391	3,834,277	10,457,668	5,344,235	3,954,356	9,298,591
Indirect costs – grants	(3,155,248)	3,155,248	—	(2,791,705)	2,791,705	—
Capitalized scientific equipment and construction projects funded by Federal and private grants	—	—	—	(68,858)	—	(68,858)
	$ 22,934,701	**12,013,129**	**34,947,830**	**20,137,941**	**11,259,930**	**31,397,871**

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